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CONTENTS

Geophysical Activity in the Oil Industry in the United States in 1947 *E. A. Eckhardt* 529

Symposium on Mining Geophysics

How Can Geophysics Be of Better Service to the Mining Industry? *C. A. Heiland* 535

Some Aspects of Ore Deposits Important in Geophysical Work *George M. Schwartz* 540

The Practical View in Geophysical Exploration for Metallic Ore Bodies *L. C. Armstrong and D. M. Davidson* 550

Some Limiting Factors and Problems of Mining Geophysics *A. A. Brant* 556

Written Discussion, Symposium on Mining Geophysics 582

Theory and Practice of Low-Frequency Electromagnetic Exploration *Haakon M. Evjen* 584

Electrical Surveys of Some Shallow Salt Domes *W. Bradley Lewis* 595

A New Method of Interpretation of Self-Potential Field Data *L. de Witte* 600

Biogeochemical Investigations in British Columbia *Harry V. Warren and Robert E. Delavault* 609

Patents 625

Reviews 639

Publications Received 642

Contributors 643

Society Round Table

Nominees for 1949-50 Executive Committee 646

Standing Committees for the Year 1948-1949 650

Membership Applications Approved for Publication 651

Announcement of Dallas Regional Meeting 654

Annual Spring Meeting, Pacific Coast Section 655

Houston Section Elects Officers 656

Deadline for Acceptance of Papers for the 1949 Annual Meeting 657

FCC Hearing on Applications for Radiolocation Licenses 657

Memorial

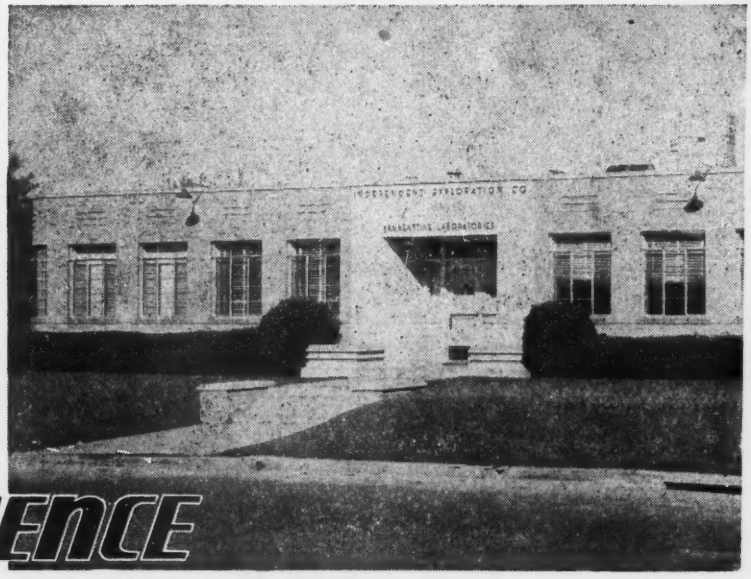
Frank Rieber, 1891-1948 659

Personal Items 662

Index to Volume XIII 664

(GEOPHYSICS is indexed regularly by *Engineering Index Incorporated.*)

45



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GEOPHYSICS

A Journal of General and Applied Geophysics

GEOPHYSICAL ACTIVITY IN THE OIL INDUSTRY IN THE UNITED STATES IN 1947*

E. A. ECKHARDT†

In 1947 the oil industry of the United States produced 2.011 billion barrels of crude oil and natural-gas liquids. The same number of barrels of new oil must be discovered in one year if the industry is to maintain its reserves. This provides a measure of the exploration job to be done.

The report for 1947 of the Committee on Petroleum Reserves of the American Petroleum Institute indicates that the job was done, with something to spare. That geophysical techniques made a major contribution to this result is hardly subject to doubt.

In 1947 the oil industry spent a minimum of $105,000,000 on geophysical work alone in prospecting for additional oil reserves within the continental boundaries of the United States. The figure may actually be substantially greater. This represents a new peak for such expenditures. Both increased units of operation and increase in unit costs contribute to the record size of the bill. The industry itself realizes, and the public must understand, that additional millions, adding up to a substantial total, were required to cover land, drilling, and other necessary exploration costs.

About ninety millions of the $105,000,000 total were spent on seismograph operations, the balance for other types of geophysical work, chiefly gravity surveys.

The steady upward trend of seismograph parties operating in the United States, which began in mid-1941, has continued through 1947 down to date with relatively minor fluctuations. In this period, the number of seismograph parties in service has more than doubled. In the face of an acute shortage of suitably trained technical personnel, this represents a truly stupendous accomplishment.

The pie chart (Fig. 3) shows the distribution of the 1947 seismograph work over the country. It is a striking fact that very nearly three-quarters of it was done in the states of Texas, Louisiana and Oklahoma. These are the very states

* Manuscript received by the Editor June 21, 1948.

† Gulf Research and Development Company, Pittsburgh, Pennsylvania.

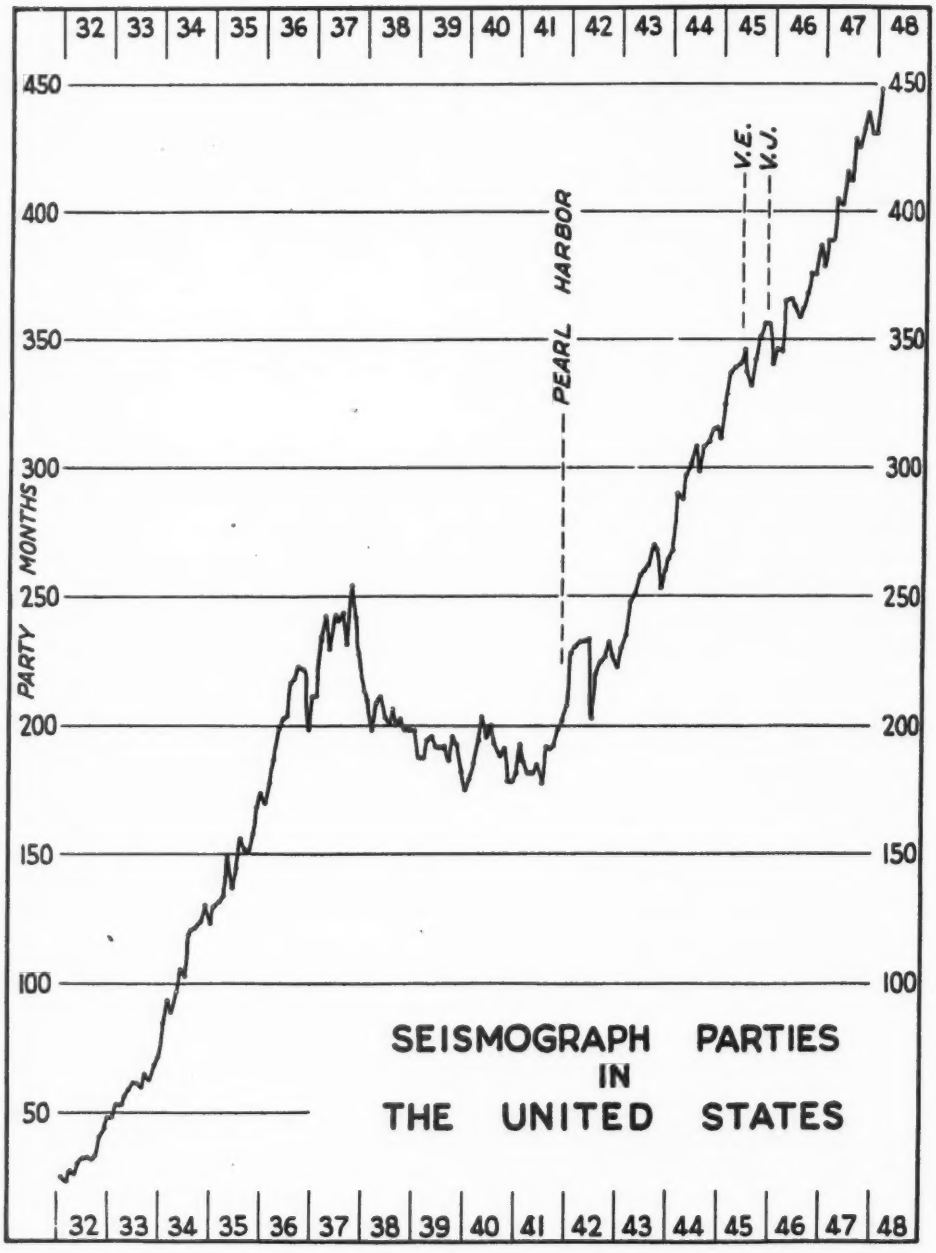

FIG. 1. Seismograph parties in the United States 1932–1947.

in which seismograph work had its beginning and early development almost 25 years ago. They are also the states which the A.P.I. Reserve Committee credits with five-sixths of all the new pool reserves discovered in the United States in 1947. The Rocky Mountain states account for about half of the remainder, the balance is scattered over the active and prospective areas elsewhere.

Special mention should be made of the off-shore seismograph work along the coasts of Louisiana and Texas. In the charts, it is included in the totals for coastal Texas and coastal Louisiana. In the former case, it represents about one-sixth of

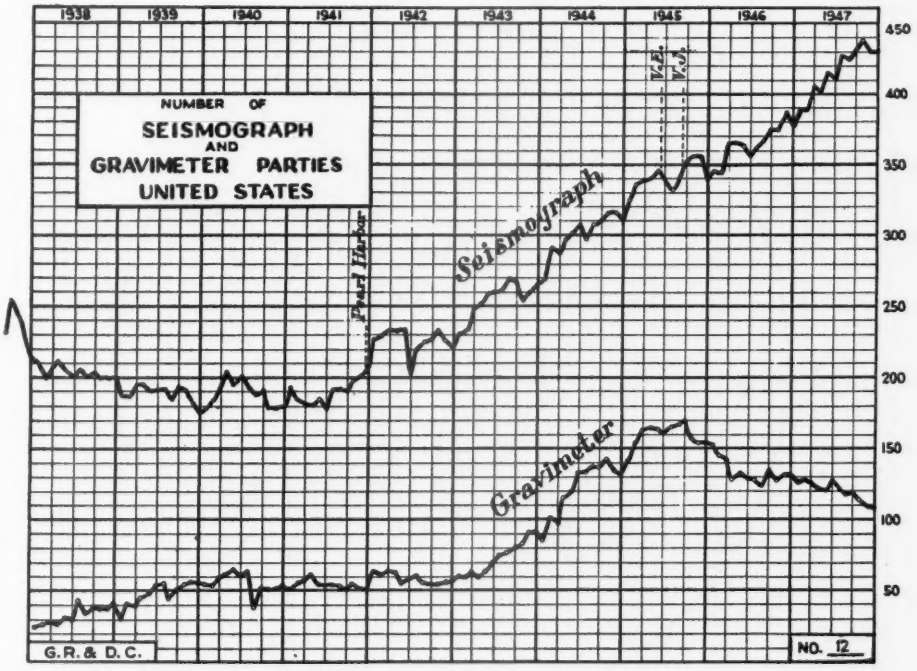

FIG. 2. Number of seismograph and gravimeter parties in the United States 1938–1947.

the total, and in the latter about one-third. This work during 1947 reached a substantially higher level compared to the preceding year.

Gravity operations followed a somewhat different pattern. For several years prior to Pearl Harbor, the gravity parties in service averaged some fifty-odd in number. In 1942 the average was slightly higher, followed in 1943, 1944, and 1945 by a spectacular rise of roughly 200 percent to a peak of 170 parties, which was reached about V-J Day. Since then, there has been a gradual and steady decline which has persisted through 1947. The average number of parties during 1947 was about 120.

About one-quarter of the 1947 gravity work in the United States was done

in the coastal areas of Texas and Louisiana, and a slightly greater amount in the inland areas of the same states. The Rocky Mountain states accounted for another quarter, and the balance was scattered as indicated in the pie chart of Figure 4.

In the case of the coastal areas of Texas and Louisiana, the gravity work done offshore represented a substantially smaller proportion of the total than was the case with the seismograph. About three-quarters of this work was done in coastal Louisiana.

Nineteen forty-seven was the first full year of commercial airborne magnetom-

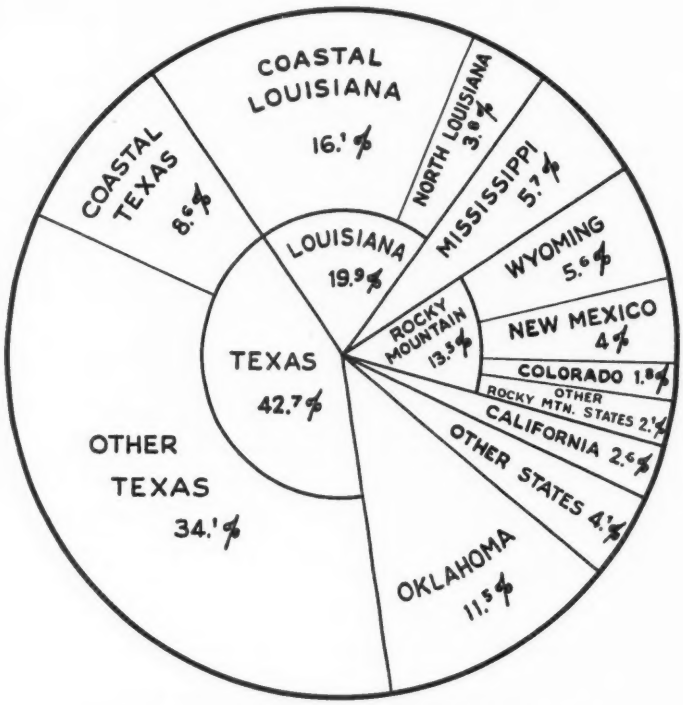

FIG. 3. Seismograph activity in the United States in 1947.

eter operations. Although the major use of this new arrival in the geophysical family occurred outside the United States, a substantial number of commercial surveys were made in eleven of the states for both oil and mining interests. The Rocky Mountain states were the scene of a substantial part of this work.

Use of this new facility may be expected to be extended and broadened as the place of this device in the general prospecting program is better understood. Experience indicates that five aircraft engaged in aeromagnetic surveying could run as much profile as did all the seismograph parties operating in the United States last year. This comparison is of value only in illustrating the high speed and low

cost with which such data can be obtained. Seismograph data and magnetic data are, in general, not competitive, but play supplementary and coordinate roles in the over-all prospecting effort. The comparison made, however, indicates that a very few aircraft will be sufficient to satisfy any conceivable demand for aeromagnetic surveys. It may be of interest to note that nine of the ten oil companies, which were the most active geophysical operators in 1938, appear in a

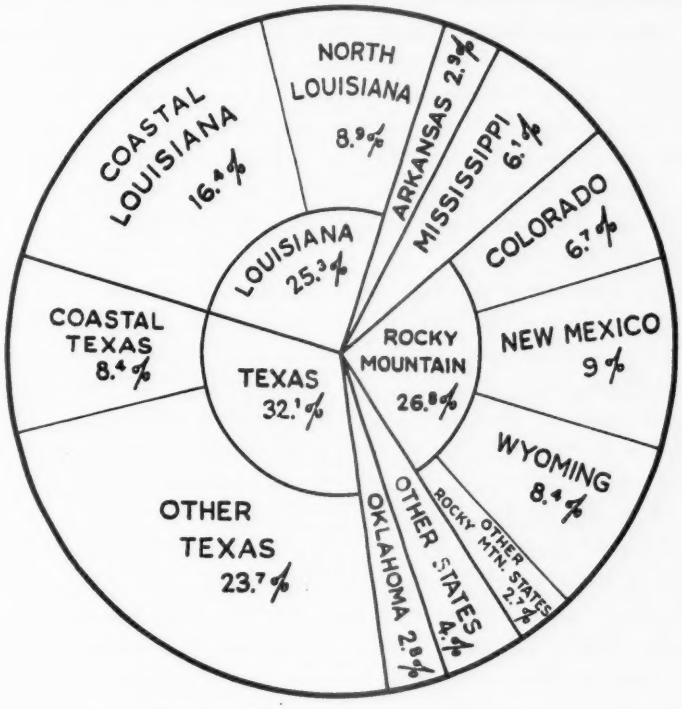

FIG. 4. Gravity operations in the United States in 1947.

similar list for 1947, and that seven of these are listed among the ten companies having the greatest U. S. reserves.

The-105-million-dollar estimate does not include the sums which have been spent in 1941 on geophysical research and development. There is no basis for estimating the amounts which have been so spent, but there is no doubt that they are measured in millions. It is not often that the results of such work lead to immediate application, and their full value is often not fully realized for several years, even by the organization which has done the work. The projects usually are based on some recognized need or some visualized advantage. They become known by the papers presented at this convention and the use made of the developments in the field. The progress of the art is strongly dependent on an adequate volume of both short- and long-range research.

In some quarters geophysicists appear to be regarded as magicians and although their pockets are not obviously bulging, one readily encounters a feeling that more white rabbits should be produced, and one hears and reads much speculation on what the next one will be like. Most geophysicists feel that they are not in the white rabbit business. For the past 25 years, they have been actively engaged in aggressively and systematically studying all physical measurements which could conceivably be made on land, sea or air and which would give information about the nature and disposition of the rocks which cannot be seen or easily exposed to view. They have devised technically sound and economically attractive means for making those measurements which are the most informative. In doing so, they have made substantial improvements in related methods of survey and transport. Genius has been defined as consisting of one part inspiration and nine parts perspiration. On this basis, the work of the geophysicists has not been lacking in genius. They have put a goodly measure of inspiration into their work and also plenty of perspiration.

Although geophysical prospecting techniques had their beginnings abroad (torsion balance, refraction seismograph), practically all important developments for the past 25 years had their origin in the United States (reflection seismograph, gravimeter, airborne magnetometer). Although data for this are hard to come by, one can safely say that, the world over, the geophysical business is dominated by Americans to a degree that few other businesses are. It seems to be a safe estimate that over 95 percent of the world's geophysical work is currently being done by U. S. geophysical organizations.

It is regretted that I am unable to give you a picture of the extent and distribution of geophysical operations abroad. It is hoped that the assembly of such information can be organized to round out the report for the current year.

For many years the bulk of the petroleum products produced in the United States will undoubtedly come from drilled wells. A major contribution to the discovery of the pools in which they will be drilled will be made by the big three of geophysical prospecting, the seismograph, the gravimeter, and the magnetometer. The procedures used have not been and will not be static. This is not to say that other techniques will not be important, but there appears no prospect at present that a fourth technique will displace any of the present leaders. There is every prospect that the volume of geophysical activity will reach a new all-time high in 1948.

SYMPOSIUM ON MINING GEOPHYSICS*

Denver, April, 1948

HOW CAN GEOPHYSICS BE OF BETTER SERVICE TO THE MINING INDUSTRY?†

C. A. HEILAND‡

ABSTRACT

By comparison with geophysical exploration for oil, geophysical prospecting in mining is of limited scope, both areawise and dollarwise. To begin with, geologic exposures are abundant in many mining districts, making the application of geophysics unnecessary. Exploration targets in mining are usually so small by comparison with the promising area that blanket exploration becomes too costly if not impossible. The geophysicist is handicapped not only by difficult transportation but difficult topography as well which in addition produces a direct effect on some of his readings. Geophysical data are difficult to interpret because of geologic complexities; to make matters worse, the methods most applicable in oil exploration such as seismic and gravimetric, are frequently of limited usefulness. A geophysicist undertaking a mining project must keep these limitations well in mind. He should not recommend the application of geophysics where no better than existing geologic information can be anticipated. If possible, he should limit the size of prospecting territory by geologic reasoning and test his methods under known conditions. Above all, he should have not only sufficient geologic training, but good geologic imagination as well when analyzing his findings. He should not oversimplify his problems nor oversell his wares. On the other hand, he should feel justified in asking a fair compensation for his services because high standards of training in both physics and geology, plus a background of long experience, are required to do a good job. The mining industry can help by supplying freely, rather than withholding, all geologic data available and by assisting in the financing of industrial research aimed at the development and perfection of new methods. Organizations specializing in geophysical mine exploration are rarely in a position to do so. Many a mining geophysicist stays with his calling not because he expects great financial returns, but because he loves his job with its variety of geophysical problems and its fascinating complexity of geology. Geophysicists in mining have committed more than their share of errors with resultant disappointment on the part of industry. However, with a better understanding of the industry's problems by the geophysicist, and the geophysicist's problems by the industry, there is no reason why the use of geophysics in mining cannot be extended.

It is a privilege to welcome you to the Symposium on Mining Geophysics sponsored by the Society of Exploration Geophysicists. Our Society was formed nearly twenty years ago by a group of men interested primarily in oil exploration. Its original name was the "Society of Petroleum Geophysicists." With an increase in membership, there appeared a broadening of interest into adjacent fields of geophysical science, engineering geophysics, and mining geophysics, and the name was changed to "Society of Exploration Geophysicists." Papers on mining geophysics have appeared in the Society's journal since 1942, although by comparison with oil-geophysics papers, their percentage has been small. At this convention, an effort has been made to assemble a group of papers dealing exclusively with mining geophysics and to discuss the broader aspects of the situation.

* The following four papers were presented at the Mining Symposium held as a part of the Annual Meeting of the Society of Exploration Geophysicists in Denver, Wednesday, April 28, 1948.

† Presented at the Annual Meeting of the S.E.G., Denver, Colorado, April 28, 1948. Manuscript received by Editor, May 24, 1948.

‡ President, Heiland Research Corp., Denver, Colorado.

We can save time and get right down to the heart of the problem by observing that by comparison with geophysical exploration for oil, the scope of geophysical work in mining is rather small. Economically, therefore, this type of work has been attractive to only a few professional geophysicists. I suspect, however, that this "character," the mining geophysicist, is not attracted to mining so much by an anticipation of great financial gains as by downright fascination and love for his subject. He loves the mountains and the streams; he loves to see "geologic stuff" other than Recent or Quaternary; he likes igneous and metamorphic rocks better than the sediments. He loves it because there is nothing simple, nothing monotonous about his geology; most every problem is different and a challenge to the imagination. Small wonder that the early pioneers in mining geophysics have stayed with their calling in spite of many disappointments.

However, to get back to the original premise: Why the limited scope of mining geophysics? Why is it that the mining industry which pioneered the use of geophysics long before the petroleum industry—back in the 1700's, to be exact—has now fallen behind in so many respects? Is it the "fascinating" geology, just referred to, or is it simply the "nature of the animal"? Is it the fault of the mining industry; is there a lack of understanding, a lack of initiative, or a wrong attitude toward geophysics? Or is it the fault of the geophysicist, his attitude toward mining problems, his frequent lack of geologic training and imagination? Has he been guilty of oversimplification and overselling? If the fault lies with the geophysicist, what can he do to improve his services?

To some considerable degree, the limited extent of geophysical exploration in mining is neither the fault of the geophysicist nor the mining industry; it is simply the "nature of the animal."

To begin with, it is evident that the use of geophysical methods is rarely called for in mining districts where the ore is not concealed by glacial drift or other non-conformable strata, i.e. in areas where there are abundant outcrops, where structure and petrography are well known, and where there is little doubt as to where the ore bodies are and how they occur in relation to host rock and structure.

Secondly, the exploration effort required in mining for a target of average size is much greater than it is in oil. Hunting for an ore body is, in many cases, like the proverbial "looking for a needle in a haystack." The reason for this is that most ore bodies have small horizontal and large vertical dimensions whereas most oil reservoirs have a large horizontal and a limited vertical extent. If you are looking for an oil anticline 4 miles long and about a mile wide and know the approximate strike direction, you may expect to find it by about 3 profiles, 2 miles apart, with a station interval of $\frac{1}{2}$ mile, in an area the size of a township. On the other hand, if you are looking for an ore body, say 1,300 feet long and 100 feet wide, you would probably need 8 profiles, about 650 feet apart, with a station interval of 50 feet. This is 850 stations per square mile, or 850 times as many stations in a township to find an ore body as to find an oil structure. Geophysical blanketing of prospects, as is customary in oil exploration, is, therefore, usually

out of the question unless the ore is associated with large-scale, regional geologic structure or host rocks of large areal extent. These may be sedimentary rocks, or lava flows intercalated with sediments or large intrusive bodies. Examples are the Witwatersrand District in South Africa, the iron ranges of Minnesota, the copper deposits of Michigan, and the bauxite deposits of Arkansas.

When it comes to a direct location of ore bodies, some geophysical methods (such as gravimetric and electrical) are handicapped not only by the lack of size of the ore body, but also by a lack of concentration and continuity of mineral substance.

A fourth and economically significant factor is that the value of the average ore discovery is less than that of the average oil pool because of different dimensions, different market price of commodity, and higher production cost. Taken in connection with the increased exploration effort required, it is readily appreciated why the *finding cost in relation to the value of discovery* is so *much greater* in mining than it is in oil. Unfortunately, we do not have any statistical figures on such relative discovery costs; in any event, they would probably be too optimistic if allowance were made for the fact that in the negative finding effort, i.e. in the elimination of prospects, mining geophysics is less efficient than oil geophysics.

Further factors limiting the application of geophysics in many mining areas are *lack of accessibility* and *terrain*. Both increase the surveying costs; besides, terrain has an adverse effect on electrical, magnetic and gravimetric methods. Corrections are laborious if not impossible, making the interpretation of the results more difficult.

Masking effects are much more common in mining than in oil exploration. They include: 1) *near-surface effects* from formations other than the host rock such as magnetite and gravel lenses in the glacial drift, conductive ground waters, and near-surface lava flows; 2) *pseudo-ore effects* resulting from magnetite, sulphide and graphite disseminations, from intrusive dikes, from bedrock ridges, from mineralized waters in shear zones or, generally speaking, from variations in the properties of the host rock.

Interpretation of geophysical mining surveys is more difficult than that of oil surveys. This is due to the greater variety of rocks in a given area and greater complexity of structure. Although we lack, in oil exploration, the direct detectability of mineral substance which is useful in some mining surveys, the structural and stratigraphic conditions are simpler since we are dealing with formations which were laid down in large sedimentary basins and therefore have horizontally uniform physical properties. Furthermore, igneous rocks, intense folding, and faulting are usually absent, and there is little or no contact and dynamometamorphism. The latter in particular has brought about in most mining areas an obliteration of density and elasticity contrasts, making the mainstays of geophysical oil prospecting, namely seismic and gravimetric methods, inapplicable in many cases.

The mining geophysicist has thus a formidable array of factors lined up against him. If he keeps these in mind, he will at least avoid the common error of oversimplification; furthermore, it will enable him to be more circumspect in the planning and execution of a geophysical survey. Therefore, he should:

1. Determine first if a survey is *economically feasible* and should *limit the size* of prospecting territory by *geologic reasoning.*

2. Examine the possibilities of *mineral associations* (gold with magnetite, and iron and copper sulphides; gold, copper and nickel ore with pyrrhotite; hematite ore with magnetite, and so forth). He should further determine the possibility of stratigraphic or *structural associations* as exemplified by the relation between the gold-bearing Witwatersrand conglomerates and the magnetic black slates elsewhere in the section. Also, an investigation of the genetic history of the deposit in question—whether syngenetic or epigenetic, auto-genetic or heterogenetic—will be of value.

3. Give more attention to physical tests of *rock specimens* which will be helpful in both the planning and in the interpreting of a geophysical survey.

4. So plan surveys that they tie in with *known conditions*, i.e. overlap into areas where the general geology and the attitude of the ore bodies are known. Sometimes it may be necessary to go outside the area of immediate interest to obtain the regional geologic and geophysical picture.

5. More than in oil exploration, consider the application of *more than one geophysical* method to eliminate interpretative uncertainties caused by the near-surface and pseudo-ore effects previously mentioned.

6. Conduct geophysical work *from underground workings* so far as possible to reduce not only the disparity between the size and distance of an ore body, but overburden interference as well.

If he attacks his problems in this fashion, the geophysicist will not only reduce the over-all cost of a geophysical survey, but will keep from proposing work in areas where the application of geophysics is either unnecessary or hopeless.

Much criticism has been leveled against the geophysicist by the mining industry in the past and much of it has been legitimate. However, the situation is not all one-sided. There have been instances where geophysical surveys have failed for lack of understanding and cooperation. If the issues involved here are fully understood, the mining industry can do much to help the geophysicist to be of better service.

One of the most common misunderstandings has to do with the very nature of geophysical work. Mining company executives, inspecting field operations of geophysical firms, have been known to exclaim: "So that is all that there is to it" and to promptly buy a magnetometer, hire an operator for as little as possible, and to give no further thought to the proper planning and evaluation of a geophysical survey. This, of course, is penny-wise and pound-foolish. In the first place, an instrument-operator is not a geophysicist. The qualifications for this job are higher in mining than in oil exploration. They include training and ex-

perience in physics, economic geology, mining, petrology, and mineralogy, plus geologic imagination and an ability to evaluate the genetic evolution of a mineral deposit from the geophysical viewpoint. Men with such qualifications should be chosen to plan, direct and interpret the geophysical work; they are not cheap and should not be afraid to ask a fair compensation for their services. They will pay for themselves many times over in the long run.

Generally speaking, a mining company should consider the cost of a geophysical survey in its proper economic perspective. First, it is well to realize that it will cost more from here on out to find our ore bodies since the ones that are indicated by surface outcrops are increasingly difficult to find. Secondly, the cost of geophysical surveys should be considered in relation to the finding costs by other methods such as diamond drilling, trenching, and shaft sinking.

Another issue on which the mining geophysicist is frequently at odds with mining companies involves their hesitancy to supply geologic information. This dates back to the days of overselling when a mining company would take the position: "If you are so good, why don't you find out what the geology is?" or: "*We* know where the ore is or should be; let's see *you* find it." This is like consulting a doctor, telling him nothing about your medical history, and leaving it up to him to find out. To be sure, it will be your money, not that of the doctor's that will be spent in experimentation unless you help him decide on a suitable treatment, where and when to operate and preferably, when *not* to operate. If a mining company employs a geophysical consultant, every effort should be made to supply him with general geologic information on the area to be surveyed. He should be supplied with rock specimens from diamond drill holes or underground workings so that he may determine the physical properties of the ore and the host rock as well; he should be allowed to test his methods under known conditions, and should be posted on the progress of concurrent geological, underground, and geophysical operations.

In conclusion, it will be observed that by comparison with oil company practice, there are but few mining companies that carry out or sponsor geophysical research. It is quite probable that the size of the average mining company and its need for geophysical work are too small to warrant individual approach. However, there is no reason why such research cannot be undertaken on a cooperative basis as is done by the agricultural and processing industries.

In this introduction to our symposium, I have had to confine my remarks of necessity to the more general aspects of the situation. To point up the topics for the round-table discussion, the Society has invited a number of papers in which mining geophysics will be discussed from the viewpoints of the geologist, the mine-exploration engineer, and the geophysicist. I am sure that you will find these papers well worth your attention.

SOME ASPECTS OF ORE DEPOSITS IMPORTANT IN GEOPHYSICAL WORK*

GEORGE M. SCHWARTZ†

ABSTRACT

The application of geophysics to mining problems is much more difficult than is the case with the petroleum industry. The fundamental contrasts between the occurrence of petroleum and ores are outlined. Difficulties arise because of the great complexity and variation in occurrence and size of deposits of commercial metallic and non-metallic minerals. These complexities are discussed and illustrations cited in terms of mineralogic, petrographic, structural, and genetic variations in ores. The relatively large horizontal extent of petroleum deposits, as compared with many mineral deposits is emphasized.

One of the important problems in the application of geophysics to ore-finding is determining the definite relation of ore to specific geologic features, so that the results of geophysical work can be interpreted in terms of the probable location of more ore. This is essentially a geologic problem, and one not easily solved in many districts. For the successful application of geophysics and interpretation of the results, a very detailed knowledge and understanding of the geology is fundamental. Also additional geophysical methods are required, particularly those which might locate ore directly rather than indirectly through the geology as is largely the case in petroleum.

Because of the complexities involved, no one method should be considered a true test of an area but several methods should be utilized. Much more extensive and intensive application of geophysics to problems of ore-finding, as well as new methods are demanded by the rapid depletion of present ore reserves.

INTRODUCTION

The ultimate purpose of the symposium, of which this paper is a part, is the stimulation of the application of geophysical techniques to the problem of the mineral industry. Geophysical methods have developed so rapidly and have been so successful in the petroleum industry that progress by the mining industry in this field seems negligent by comparison. One is immediately confronted, however, with the question as to what extent methods found useful in petroleum exploration may logically be applied to the search for minerals. It is pertinent, therefore, to make some comparisons and contrasts between the problems of exploration in the two fields.

One of the prime difficulties in the application of geophysics to mineral problems is the fact that few geophysicists know enough economic geology, and certainly few economic geologists and mining engineers know enough geophysics, to be able to work in the field to the best advantage. Therefore, a symposium of this sort is particularly worthwhile because the viewpoint and ideas of each group may be presented and discussed to their mutual advantage.

The writer previously has stated to one of the national committees the opinion that ore-finding in the future must depend more and more on geophysical and perhaps geochemical methods. Not only must present methods be used, but new and better methods should be developed to aid in the search for the enormous

* Presented at the Annual Meeting of the Society, April 28, 1948, Denver Colorado. Manuscript received by the Editor March 26, 1948.

† University of Minnesota.

quantities of metals that will be needed to maintain our present standard of living even for the next half century.

In this paper the emphasis laid on the complexities and difficulties of using geophysical methods in the search for ore should not be interpreted as an argument against geophysics. It is rather to lay a foundation for a realistic approach to the problem. The largest item in the 1947 and 1948 budgets of the Minnesota Geological Survey, of which the writer is Director, pertains to cooperative magnetometer work with the United States Geological Survey. Most of the northern part of the state is to be covered with airborne traverses at intervals of one mile. Fortunately, magnetic work is particularly applicable to the search for ore in Minnesota as shown by the discovery of the Cuyuna district in 1906, largely through evidence furnished by the dip needle and sundial compass. The airborne magnetic method is an example of the large-scale approach to mineral exploration that should be widely favored. It is unfortunate that we do not have several other methods as easily applied on a large scale.

In considering the problem of application of geophysics to the discovery of economic minerals, one might begin by reviewing the five criteria which a usable geophysical method must satisfy as given by W. M. Rust, Jr., in his Presidential Address before the Society of Exploration Geophysicists on April 4, 1945.

1. The method must involve physical measurements of some property of the earth.
2. The measurements must give reproducible results.
3. The process must be able to compete, on the basis of economics, with existing methods.
4. The method must have a significant relation to the occurrence of oil (economic minerals).
5. The method must have a teachable interpretation.

FUNDAMENTAL CONTRASTS IN THE OCCURRENCE OF PETROLEUM AND ECONOMIC MINERALS

It is no doubt stating the obvious to emphasize the contrast between the occurrence of petroleum and of many economic minerals, particularly metallic minerals; but nevertheless the fundamental differences are not always kept in mind. The occurrence of petroleum is relatively simple, meaning that it is fairly consistent in its geologic environment. It is fluid or gaseous and is mostly restricted to sedimentary rocks that have undergone little metamorphism. The reservoir rock is porous and permeable and the confining rocks impermeable. Petroleum normally occurs in elevated structures and these are ordinarily less complex than many ore-bearing structures. The environment is therefore definite and can be evaluated fairly well. Geophysical methods have accordingly been conspicuously successful in locating favorable environments for oil and gas.

The problems of the mineral industry are complicated by the fact that there are a great many different ores and economic products of very different charac-

teristics. Reference to the table of contents of a standard text on economic geology shows that there are about 25 metals deserving discussion and an equal number of non-metallic products. In short, in petroleum problems, we have a liquid and a gas phase; in metal mining alone, there are 25 elements, many of which occur in several solid phases, that is, as minerals.

The occurrence of mineral deposits is so complicated that for the sake of clarity it will be essential to discuss the problem under some sort of systematic headings. It may be logical to start with the fundamental constitution of ores and pass on to the larger features, indicating in each some aspects of possible importance in geophysical work. The treatment is by no means exhaustive and the complexities listed here could be easily augmented, but it does not appear necessary to labor the issue.

MINERALOGICAL VARIETY IN ORES

There are over 200 metallic minerals, and of these approximately 100 occur in commercial ores with enough frequency to be important in the production of metal. There are perhaps 2,000 non-metallic minerals, of which fully 100 are of some commercial importance.

These economic minerals include sulphides, oxides, sulphates, carbonates, chlorides, silicates, phosphates, and native metals, as well as less common compounds. They vary greatly in specific gravity, magnetic susceptibility, electrical conductivity, chemical activity, radioactivity, and in the less evident properties. The variation in properties in turn determines the effects which may be measured by various geophysical methods.

Iron minerals furnish the most obvious example of the importance of a physical property. If even a small amount of magnetite is present in a rock, a strong magnetic effect is set up. If, on the contrary, iron is present only as siderite, hematite, limonite, or most iron-bearing minerals other than magnetite and pyrrhotite, there is little or no effect beyond that of most common minerals. On the Mesabi range the actual ore has comparatively little magnetic effect, whereas the taconite protore has an extremely high magnetic susceptibility. This contrast is a result of the fact that commercial ore has been formed by oxidation of magnetite and siderite, the important iron minerals of the taconite, and by the leaching of silica from the taconite.

Some ores, particularly gold, copper, and nickel, have large amounts of associated weakly magnetic pyrrhotite, and such deposits may be investigated by magnetic methods. Pyrrhotite varies considerably in its magnetic susceptibility and caution must be used where it is present. Magnetite is often associated with pyrrhotite, and some pyrrhotite-bearing ores which give strong magnetic effects may actually owe much of this effect to magnetite. Many other large gold and copper deposits are lacking in minerals with appreciable magnetic effect. More specifically, copper deposits at Ducktown, Noranda, and Flin Flon give strong magnetic effects, whereas existing knowledge of the character of the disseminated

ores of Utah Copper, Morenci, Chino, Ray and Miami districts, leads to the conclusion that they would provide abnormally low attraction. The weak magnetic effects of the latter deposits result from the destruction of magnetite in the original porphyry by hydrothermal alteration that accompanied introduction of copper.

Another characteristic of pyrrhotite probably is significant in connection with geophysical work. It is easily altered by meteoric solutions and therefore breaks down rapidly to form sulphuric acid with a corresponding tendency for electrical currents to be set up. The same may be said for marcasite.

Ore bodies composed of massive metallic sulphides have a specific gravity about double that of adjacent wall rocks. The possibility of searching for this type of ore body by gravimetric methods would seem to be worth investigation. Most sulphide ore bodies, however, are not sufficiently concentrated to provide measurable gravity anamolies except when relatively close to the surface. It would also be difficult to tell whether a deposit is large and deep lying or small and near the surface. Iron ore deposits of high grade furnish the necessary conditions for gravimetric attack. The writer has been informed that gravimetric work on the Steep Rock Lake iron deposit in Canada last summer was successful.

It is evident that the mineralogic variety of ores complicates the application of geophysics to mining problems. There is the favorable aspect that different minerals may permit the application of different methods. This would, in turn, emphasize the obvious fact that an adequate knowledge of the mineralogy of ores is a necessary prerequisite to geophysical exploration. One should at least know what kinds of minerals occur in the ores, as well as have some knowledge of the quantity of ore that is likely to occur, based on data in other areas. The geophysical methods most likely to yield valuable information could be, in part, inferred from the mineralogy.

It should be emphasized that minor constituents may be important, and if methods based on radioactivity prove successful, very minute constituents will be important.

PETROGRAPHIC VARIETY IN ORE OCCURRENCES

The fact has been noted that oil and gas occur in limited varieties of rocks, essentially sandstone and carbonate rocks. In contrast, ores occur in almost every common rock type, and any teacher of economic geology could cite offhand illustrations for each type.

Another problem is the fact that an igneous rock mass may be significant as indicating the deep magmatic source from which the ore solutions originated, but the ore itself may be largely in the adjacent rocks. Examples are the enormous amount of ore in the limestone around the Sacramento stock at Bisbee; or the extensive ore bodies in schist and limestone of the Globe-Miami district where the Schultze granite (quartz-monzonite) is presumed to represent the source of the solutions. In other districts the ore has been introduced into an igneous rock

formed long before, for instance, the portion of the San Manuel deposit in Arizona that is in the pre-Cambrian Oracle Granite (quartz monzonite).

In contrast, the porphyry of the disseminated copper deposits is not only the host rock, but is the visible expression of the magmatic source of the ore-bearing solutions. Needless to say the variations in relations are important in the interpretation of geophysical data obtained in any district.

Inasmuch as ore may occur in almost any kind of rock, it is evident that the variations in the physical properties of rocks are important. Specific gravity, porosity, permeability, electrical conductivity, magnetic permeability, elasticity, rigidity, and radiations vary greatly. Some of these variations may help in geophysical work, particularly where they can be outlined in a simple manner. They cause difficulty because they are so varied. In all cases there is the problem of the known, or theoretical, relation of the ore to any one of these variable factors. This is often difficult, and sometimes impossible, to determine with the data at hand. More intensive geologic studies than we have been accustomed to make would seem to be required as a proper basis for geophysical work. Ores may, or may not, be confined to a single rock type in a given area. Occurrence in several kinds of rocks within a district might be cited by the score but a few examples will suffice.

The great gold deposits of the Homestake mine in South Dakota occur in a pre-Cambrian formation that varies from cummingtonite to chlorite schist. Within the pre-Cambrian rocks, gold seems to be rather strictly confined to this highly favorable bed. However, in adjacent areas, some only a few hundred feet away, gold occurs in Cambrian dolomite and sandstone that are highly silicified but otherwise are unmetamorphosed. A few miles away gold has also been produced from porphyry.

Many mining districts of the western United States have copper ore in limestone, in porphyry intruding the limestone, and lesser amounts in other rocks. The Bingham, Bisbee, Ely, Morenci, and Globe-Miami districts are good examples. At Ray and Miami, ore occurs in porphyry, and more abundantly in the schist intruded by the porphyry. At Bingham, ore occurs in quartzite as well as in limestone and porphyry.

The Calumet and Hecla copper ore occurred in conglomerate, but most of the other mines of the Keweenaw district had ore in brecciated amygdaloidal tops of basalt lava flows. At White Pine near the south end of the district, however, copper occurs in shale and sandstone. Consider the variation in physical properties between shale, sandstone, conglomerate and amygdaloidal basalt. The conglomerate, incidentally, is composed of felsite, not basalt pebbles. The native copper made up only one or two percent of the rock for the most part so that the rock, not the copper, would dominate the physical effects.

Perhaps these examples emphasize the negative too strongly because in some districts the ore does occur mainly or entirely in one kind of rock. At Butte it is

quartz monzonite; in the Mississippi Valley lead-zinc deposits, it is limestone. No doubt geophysical problems will be easier to solve in districts where the ore is restricted to one rock type. However, the geologist and geophysicist are always confronted with the question: Is the ore really confined to one rock type? There have been numerous examples where this was thought to be the case, but ore was later found in other rocks. In prospecting an unknown area, it would seem necessary to consider the possibility of ore in almost any rock type, although certain types, such as limestone, would be considered more favorable.

Not only the petrographic variations, but the relation to specific formations raises problems. In some districts the ore is related to a single formation. Other formations that are barren may be later than the ore. Where this relation can be proven, it may be of considerable help in ore finding, both by geologic and geophysical methods. Determination of the thickness of barren material overlying possible ore-bearing rocks is a problem that should be readily solved by geophysical methods.

There are districts, however, where the ore pays little attention to formations. The Magma mine at Superior, Arizona furnishes a good illustration. This remarkable vein has been followed for nearly 6,000 feet horizontally and 5,000 feet vertically. It crosses Devonian, Cambrian, and a thick section of pre-Cambrian rocks essentially without change. The rocks involved include: limestone, quartzite, basalt, diabase, conglomerate and schist.

At Bisbee ore bodies have been found nearly from top to bottom of 3,000 feet of limestone involving formations of Cambrian, Devonian, and Carboniferous age. In some parts of the district one formation is most productive, in adjacent parts another formation. It is easy to visualize the difficulties of both geologic and geophysical exploration under such conditions. This emphasizes the need for methods which will detect ore directly and not indirectly by means of identifying supposedly favorable formations and structures.

Relatively insignificant differences in rocks may sometimes greatly change their effect on geophysical measurements. Many years ago the writer traced a narrow magnetic zone of great intensity for several miles, wondering what could be responsible. Finally a small creek exposed the source, a small sill of black diabase not over 3 feet thick. Even microscopic examination failed to reveal more than the normal amount of magnetite for a diabase. Presumably the mass was polarized to give an exceptionally strong attraction. Such unusual features only cause trouble, as they are rarely connected with ores.

Geophysical methods, as has long been known, are useful in mapping formation boundaries. The writer's attention recently was called to a small syenite stock in northern Minnesota[1] whose contact was definitely outlined by an ordinary dip-needle survey in 1919. The mass was known from only a few outcrops and

[1] F. F. Grout, "The Geology and Magnetite Deposits of Northern St. Louis County, Minnesota," *Minnesota Geological Survey Bulletin 21* (1926), p. 208.

none of these exposed a contact. Where applicable, this use of geophysical methods should continue to be helpful and no doubt should be used to a greater extent than heretofore.

STRUCTURAL CONTROL OF ORES

Rock structures play a very important role in the localization of both petroleum and epigenetic mineral deposits. The difference is that, whereas petroleum is mostly localized in elevated structures, almost every kind of known structure has at some place localized or helped to localize epigenetic minerals. Bedding planes of horizontal or folded strata, joints, faults, brecciated zones, volcanic and breccia pipes, vesicular and brecciated tops of lava flows as well as various combinations are important.

In some districts the relationship of ore to specific structures is so definite that geophysical methods which determine structure have helped greatly in the search for ore. In other districts the relation to structure is so indefinite or inconsistent that it provides only a meager aid in the search for new ore. The difficulty is not so much with geophysics as it is with our knowledge of the geology. It is perhaps unfair to blame the geologist because the real trouble lies in the fact that ore deposits sometimes have formed without leaving concrete evidence of how the material got in, or why it was deposited in that particular area. It is no doubt true that most epigenetic deposits have been localized by structure, but to determine the exact structure responsible is often difficult, or impossible. Some large massive deposits, such as those at Noranda, Quebec and Jerome, Arizona, have lensed out downward but with no evidence at the bottom as to where the solutions entered the mineralized area. At least this was presumed to be the case according to the latest information available to the writer.

It is perhaps unnecessary to argue that the application of geophysics to ore finding would be much more successful if ore deposition were controlled by some simple structural relation. Because of the complicated relations which do exist, the necessity for detailed geologic work is again emphasized.

Before leaving the subject of structure, one fundamental difference between the occurrence of petroleum and of many ore deposits should be emphasized. Petroleum occurs with the largest dimensions of the reservoir spread out nearly horizontally. This gives a fairly large target for both geophysical methods and drilling. Many ore deposits, in contrast, have large vertical dimensions and relatively small horizontal extent. They present a small target and methods of location must be rather precise. This obviously does not apply to all ore deposits but nevertheless, the principle is important.

It should also be emphasized that geophysical methods, such as seismograph surveys, work best on simple and rather large structures. Much difficulty has been encountered where the structure is relatively complex. Considering the great structural complexity of the occurrence of many ores, it is only being realistic to admit the difficulties involved.

VARIATIONS IN GENESIS

Syngenetic versus epigenetic deposits.—The subdivision of mineral deposits into those formed with the enclosing rocks and those introduced at a later time provides a convenient basis for a consideration of problems of exploration. Deposits. formed at the same time as, or nearly contemporaneously with, the enclosing rocks are bound to have a definite and relative simplicity of occurrence that greatly aids exploration. The general problems are perhaps more like those encountered in petroleum geology. The Clinton iron ores serve as a specific example.

Much of the complexity of mineral deposits, particularly those of the metals, is a direct result of their epigenetic origin. Solutions and gases carrying the valuable elements, together with the material which forms the gangue, pass through many kinds of rocks and are eventually deposited where physical-chemical conditions are suitable.

Some of the factors that determine precipitation are pressure, temperature, concentration, chemical and physical character of the host rocks, and mingling with other solutions. Differing combinations of these factors furnish an extremely wide range of favorable situations with the resulting variety in the deposits. Unfortunately, it is difficult to determine in a given case which factor or combination of factors caused precipitation. It is, therefore, difficult to draw inferences as to the logical place to look for ore. Geophysical methods may often enable precise determination of geologic factors, but if inferences as to the significance of the factors are vague, little practical value results. This has long been recognized in magnetic work. It is comparatively easy to map the magnetic variation in an area, and detail is limited mainly by time and money. To infer where iron ore or even an iron-bearing unit will be found is not so easy, because too many kinds of rocks have a similar magnetic attraction. Basic igneous rocks practically always contain enough magnetite to give rather strong magnetic effects.

Temperature and Pressure zones.—Geologic theory as to the importance of temperature, pressure and depth in the genesis of ore deposits has varied greatly. It is, however, evident that the conditions under which ores are deposited have a very wide range. Take the problem of depth of formation. Conditions at the time of deposition are not necessarily the same at a given depth, but there is plenty of evidence that ores have formed all the way from the surface to depths of several miles. Furthermore, there is much evidence that temperatures at the time of deposition have varied greatly and result in distinctly different mineral assemblages. Deposits of the different depth and temperature zones vary widely in their characteristics as witness the fact that Lindgren used both categories in his classification of epigenetic mineral deposits. Emphasis was first on depth, later on temperature. Each class, that is hypo-, meso-, and epithermal, has varying characteristics of importance in geophysical prospecting.

Weathering and Enrichment.—The process of weathering has an extremley important and varied effect on many mineral deposits. These changes, in turn, have a marked effect on geophysical problems which arise in connection with the deposits. One of the most obvious variables is the depth of weathering, which ordinarily is related to the existing water table. In some deposits, however, the present water table evidently bears little or no relation to the bottom of the weathered zone. For example, in the recently explored San Manuel deposit at Tiger, Arizona, the water table exists at depths of from 300 to 800 feet, depending on the surface elevation and location with respect to the San Pedro River Valley. The bottom of the oxide zone varies from 285 to 1,630 feet in depth. The oxidation of the ore evidently not only took place before the establishment of the present water table, but preceded extensive deformation which tilted the oxide zone. Needless to say, such a complicated relation of water table, oxide, secondary sulphide and primary sulphide zones would have rendered extremely difficult the interpretation of geophysical data for the area, had such been available previous to the drilling.

Even in relatively simple cases, the thickness of the weathered zone is important and where the thickness is great, as in many arid regions, the difficulties will increase roughly in proportion to the square of the depth to the sulphide ore.

A great deal depends on the amount of oxidation and other chemical activity going on at the present time. The strength of ground currents depends on activity at the present time rather than the amount of previous oxidation. In some arid regions it may reasonably be inferred that present-day activity is restricted due to a lack of ground water although activity extends to great depths in most arid regions.

TOPOGRAPHY

Inasmuch as the present discussion is largely concerned with the difficulties of applying geophysics to mining as compared with petroleum, it is desirable to call attention to the problem of topography. Petroleum certainly is not confined to relatively level country, but it is a fact that the areas of greatest production are mainly in the plains in contrast with the occurrence of a considerable portion of mineral production in mountainous areas. The very nature of the epigenetic origin of mineral deposits makes them numerous in mountainous areas.

In the case of gravity work, topography is so important that one may suspect that calculating out the effect of topography in a rugged mountainous area would be a formidable task. It is no doubt true that rugged topography introduces considerable difficulty in the application of practically all geophysical methods, not to mention the extra expense involved. This, I believe, has been amply demonstrated by geophysical work in the oil fields.

GENERAL CONCLUSIONS

The complexities and difficulties of the application of geophysics to the discovery of mineral deposits has been dwelt on at some length. If we accept the

reality of these problems and the necessity for their solution, the question remains as to the proper mode of attack. Several suggestions may be made.

First, it should be recognized that no piecemeal attack on these problems is likely to be successful. We need a broad program of fundamental research which will explore and develop every possible line of attack. This need not be confined to geophysics but should include geochemistry and, of course, geology. Geophysical methods are badly needed which will detect the presence of the ore directly and not depend on inference from structure, stratigraphy or rock alteration. These latter should not be neglected but their path to ore is devious and not easily followed in many districts. Of course, the mining geologist is not alone in hoping for direct methods; workers in petroleum have long expressed the same desire.

Broad regional studies are needed, not just coverage of small areas in or near mineralized districts. Such limited data are difficult to analyze without the regional framework. The aeromagnetic work in Minnesota is an example of the type of work in mind. Practically the entire northern part of the state will be mapped by traverses a mile apart as a basis for detailed work. It is understood that the entire state of Indiana is to be covered in a similar manner, doubtless with the occurrence of petroleum in mind.

The task is large and support must be in proportion. The mining companies should band together to support the project or perhaps it would be more practical to assign the task to the Federal Government. In any event, support for an adequate program must be urged by industry in no uncertain terms or sufficient funds will never be forthcoming. Numerous agencies are at work on the problems of natural resources; perhaps if there is vigorous support behind an adequate program, something definite will result. Present shortages are a warning that time is short, and the path to success is long and devious, as has been emphasized in this paper.

THE PRACTICAL VIEW IN GEOPHYSICAL EXPLORATION FOR METALLIC ORE BODIES*

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ABSTRACT

This is a nontechnical paper dealing with the potentialities of geophysical methods in the search for metallic ore bodies which do not outcrop. It emphasizes what exploration engineers are entitled to expect as well as to demand from geophysical surveys.

Harmful misconceptions and frustrations have arisen among mining men through lack of understanding of the possibilities of the various methods, and through confusion traceable to the loose claims and looser interpretation of results on the part of some geophysical surveyors. The miner should be made to understand that geophysical methods merely measure physical effects, either inherent, or induced, in various rock bodies, and that high geological competence is usually needed to judge whether anomalous measurements may be correlative with ore, likely ore-bearing structures or with features totally unrelated to ore occurrences. Since they do not put any tags on ore bodies, as some have been led to believe, the capabilities and limitations of the methods need further clarification.

The biggest hurdles to overcome before geophysics can reach a fuller measure of its true potentialities in ore finding are, first, the development of techniques for mitigating or eliminating the anomalous effects of overburden; second, development of methods for detection of disseminated metallic sulphide deposits; third, perfection of techniques of investigating the rocks surrounding bore holes for appreciable distances; fourth, the improvement of techniques for geophysical prospecting underground; fifth, independent consultation before a survey is started to weigh dispassionately the chances for success (geophysical surveys should be checked with much pains and precision by repeating traverses and readings); sixth, reduction in costs for all methods; and seventh, modification and improvement in efficiency of equipment with special attention to increasing depth range.

Finally, there is a critical need for research, long-range, indirect, fundamental research, as well as direct research on known ore deposits which have not been disturbed too much by development or mining. This latter will be most profitably carried out if undertaken by private mining companies on their own properties and with complete cooperation from their own geological staffs.

The need for greater reserves of ores of nearly all the metals is now generally recognized, and it is also recognized that these new deposits must come largely through the discovery of deeper seated ore bodies having no surface exposure. These will be found by plumbing the depths of the earth, and, in this endeavor, geophysical methods should and can be of material aid.

Although geophysics has a well-established reputation in the petroleum industry, it has not been so successful in its application to mineral exploration and is not widely accepted as a useful tool by mining men. Among the explanations given for this failure is the small size and greater complexities of ore deposits and related structures as compared to those associated with oil. The problems are far different from those which confront the oil geologist. The matter is probing for possible oil traps in deep-seated structures, and his targets are broad and comparatively flat-lying. In contrast, the miner searches for a prize which is relatively near the surface and, in many places, is a steeply inclined, tabular body. Near-surface anomalies, then, while not affecting too much the broad interpretation made

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by the oil geologist, are definitely great hindrances in the examination and interpretation of anomalies which may relate to relatively shallow-lying metallic lodes. For instance, an oil geologist searching for a possible deep-seated magnetic ridge in pre-Cambrian complex will have little difficulty in distinguishing between an anomaly arising therefrom and one arising from magnetic sands buried in a now concealed former glacial river channel. However, the magnetic sands in this glacial river channel could very effectively prevent or confuse the proper interpretation of a near-surface magnetic ore body.

With some justification, the mining fraternity has in the past had feelings of frustration in trying to appraise the possible value of geophysical surveys. Those of us who have followed the course of geophysical surveys over the past twenty years have witnessed the trial of certain methods in several parts of the world which have, in spite of the rather large claims made by their proponents, failed to produce the promised results. Some of us have witnessed a repeat performance, using exactly the same methods in the same places and with the same disappointing end. In one extreme case we have even seen a third unsuccessful attempt. In consideration of such a history, it is no wonder that some mining men are pessimists with regard to the possibilities of success in geophysical exploration. A part of this feeling may be traceable to a misunderstanding of the scope of the survey and the limitations of the methods employed. In some of these trials, the client, through misinformation and an improper conception of the capabilities of the method, sanctioned the survey with the thought that it would be directly definitive of ore, whereas at best, it could only be indicative of structures which may have controlled the localization of ore minerals.

Fortunately, precautionary measures are now available to those considering the advisability of an expensive geophysical survey. There is now a good supply of experienced, reliable geophysical consultants. They are men of the highest professional integrity and ability, and their advice should be sought before a survey is undertaken. Mining engineers are prone to criticize laymen who call in the mining engineer or geologist after a mine has exhausted its ore. The exploration engineer in turn lays himself open to similar criticism when he employs a geophysical firm without taking advantage of the expert consulting advice now available. The doctor should be called in before the patient dies.

In the search for blind ore bodies, the problems introduced by the presence of overburden are of paramount concern. Where the sought-for lodes lie at no great depth and are capped and enclosed entirely by rock with reasonably uniform properties, the probability of discovery by geophysical means is high. However, we are faced in many cases with the task of ore hunting in places where the challenging conditions are those wherein bedrock is concealed by a thick mantel of overburden composed of a variety of rock fragments, ranging in size from clay to boulders, and containing local concentrations of magnetic sands. The chance for satisfactory geophysical prospecting may be further beclouded in certain sections by water courses and by saturation of this unconsolidated material by electrolyte-bearing waters.

Overburden in glaciated regions offers still another hazard inasmuch as there is a lack of conformity between the existing topography and the contour of the bedrock surface. Ridges buried under glacial till often produce anomalies which either mask or are indistinguishable from effects having their true roots in the bedrock.

The whole problem of detecting and eliminating the disturbing influences of overburden is most vitally important. It will not be easy to solve and deserves a number of methods of attack, both theoretical and practical. If we cannot reach a successful solution in this, we shall have lost a major part of the potential usefulness of geophysics in metalliferous exploration.

Another of the greatest needs confronting geophysical exploration is for the development of instruments and techniques designed for the express purpose of finding bodies of disseminated metallic sulphide. This kind of ore occurrence is one of the major sources of metals throughout the world, but in some districts we know that in spite of their vast extent only a small portion of these deposits are exposed at the surface, and in all likelihood tremendous bodies exist which have no telltale surface trace. The obligation rests heavily on geophysicists and geologists alike to devise means for the unearthing of this type of occurrence. The detection of disseminated deposits like the porphyry coppers, the exploitation of whose vast wealth helped substantially to contribute so greatly to American power, constitutes one of the foremost challenges to our scientific ingenuity.

Heretofore, geophysical surveys have been confined mostly to tests conducted from the surface, but there is no valid reason why they should not be carried out underground, nor should we fail to take advantage of the the opportunities for geophysical surveys provided by bore holes in sounding out their possibilities for detecting the presence of buried ore deposits. It has ever been a sore point with the exploration engineer that drill holes test only the rock through which they actually penetrate. A 1,000-foot drill hole may cost several thousand dollars, yet all the engineer gets for his money is a thin column of cylindrical rock known as a core and, regrettably, all too often this is woefully incomplete.

Headway is being made now, and much more can be accomplished in enlarging the effective radius of bore holes by sounding out the surrounding rock and investigating the area between bore holes. It should be pointed out here that studies made from underground openings, or bore holes, would be free from the considerable problem of anomalies arising from conditions in the overburden.

With time and intelligently directed effort a great deal will be accomplished in the way of extending the depth range for all geophysical methods. Nevertheless, most geologists would probably agree that if we could only count on exploring adequately the depth range down to 500 feet below surface, the ore possibilities exposed therein would be sufficient for this generation. For the time being, then, it would be as well for us to sharpen our tools for ore search within this zone rather than to dissipate our efforts in attempts to probe to much greater depths.

Along with technical improvements, there must be a substantial reduction in the charges for geophysical work. With the newer types of light-weight gravity meters, the cost of gravity surveys can be reduced to a scale comparable with magnetic work. Also, for the kind of seismic survey which would be applicable in underground exploration, light equipment and small power units could be constructed and put into operation for but a small fraction of the cost of the larger equipment and crews needed in oil exploration.

In addition, there are compelling economic reasons which demand that the cost for geophysical surveys for mining exploration be substantially lower than those for oil investigation. The miner cannot afford to pay as much for this service as the oil man. This is a reflection of the difference in the relative economics of the enterprises involved. The oil prospector seeks for conditions wherein may exist widespread oil pools having many years of life from which production will take place through the same drill hole by which the mineral supply was discovered. It may be rightly stated, that once his mineral wealth is located, his cost of development and his cost of mining are negligible compared to the value of his product. Contrariwise, the miner, if and when he is fortunate enough to find promising occurrences of metal by drilling, then must contemplate an expensive and arduous program of shaft sinking and underground development, after which he visualizes, providing an economic ore body is proved up, a recurrent and relatively substantial charge for the extraction of his product. Thus, when advocates of geophysical surveys point out that oil men have spent hundreds of millions as against hundreds of thousands expended by the mining people for geophysics, it is hardly a fair comparison. The deposits of raw materials exploited by these two branches of the mineral industry differ greatly in size, properties (liquid vs. solid), and in relative cost per unit mined, treated, and delivered to the ultimate market. Clearly this inequality in the economics of the two bears a direct relation to what each can disburse for the location of new supplies.

Finally, there is the all-important matter of research. We shall make no substantial progress in ore finding by geophysics without improvement in methods and techniques. First, there must be long-range, fundamental study of the physics of the earth's crust and of the application of various methods to the measurement of anomalies caused by metalliferous lodes. Some work has been carried out in this direction by the more forward-looking geophysical firms, but these have been handicapped by lack of adequate funds and personnel. The burden of this phase of research should rest on the more substantial mining companies, and to a great extent, also, on the United States Geological Survey. It devolves on this organization, as part of its rightful function, to carry on experiments of a nature and scale which would be denied most private concerns, but which will contribute materially to the ultimate knowledge and specific usefulness of mining geophysics.

A more immediately important and direct phase of research relates to the measurement of known ore bodies and their environs by all the appropriate geo-

physical methods. There has been marked neglect in this direction, but it seems likely that we would prepare the way for much greater progress, if all methods were exhaustively tested in this manner. Here again, it appears probable that our foresighted mining concerns can make great contributions, and here again, too, the Geological Survey can help immeasurably. It is of the utmost importance to the industry that the results of these surveys be made public, as concerted studies such as these will advance mining geophysics in direct proportion to the information made available.

An appeal should also be made for greater cooperation between mining geologists and geophysicists. The problem of ore discovery is difficult enough without adding to it by erecting blockades to the free exchange of knowledge. Members of both professions have erred in not giving complete, honest assistance to each other. One group has in some cases allowed guesses to pass unqualifiedly as facts, and the other has too often withheld essential information.

Certain instances come to mind in which the geophysicist has placed himself in a mathematic aura that has made it almost impossible for the client to follow his field procedures and to evaluate his findings. There is little justification for this. The concepts and mathematics are not too complex; the principal complications are those introduced by the mode of distribution of rock masses in the earth's crust. The geophysicist should, therefore, be able to discuss his work and to interpret and display the results of his speculations in everyday terms which can be understood by the man who must weigh all factors bearing on the chances for success of the project.

On the other hand, geologists and engineers have not been blameless. Too frequently, their attitude toward geophysics has been too much one of mistrust, and resultingly, the geophysicist has often been assigned to investigate a given area without recourse to vital geological data. Furthermore, we have not taken even the ordinary precautionary measures for checking which we would have carried out in sampling a cross-cut. There are simple common-sense yardsticks available for measuring the reliability of various geophysical determinations. For instance, the system of looping in magnetic and gravity surveys provides a very satisfactory, reliable test for checking these determinations. If these looping tests are conducted on different days, they serve to increase confidence in results, if check readings are satisfactory. In electrical surveys, the traverse lines can also be checked by running duplicate traverses, thereby providing readings which, if confirmatory, increase confidence, whereas, if they differ too markedly, one can with all justification conclude that the survey is not applicable to the problem in hand.

In the future quest for deep-seated ores, there should be no sharp division of responsibilities between geologist and geophysicist, except in those phases of the project in which one or the other is eminently more qualified to assume control. The selection of favorable sites should lie largely in the geologist's domain, whereas the burden of choice of applicable methods and efficient field techniques should

rest for the most part on the geophysicist. It is clear that the rationalization of basic data calls for the best cooperative efforts of both members of the exploration team. It is also evident that geophysical forecasting, like geological prediction, can never be entirely free from error. For this reason, it would seem wise never to regard the interpretations of results as finished business; they should be reviewed in the light of each new bit of geological control and revised when necessary. With this pooling of knowledge and skills and with improvement of tools and methods, it is felt that venture capital will be given the highest type of service per dollar risked. The geologist and geophysicist must work together in a mutually friendly, cooperative spirit if we are to achieve success in the great search to replenish our mineral wealth.

SOME LIMITING FACTORS AND PROBLEMS OF MINING GEOPHYSICS*

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ABSTRACT

The force-field methods, magnetic, electrical resistivity and equipotential, self-potential, electromagnetic, gravimetric and geothermal, where the forces observed result from the action of natural or artificial fields are all limited by the decrease in anomaly according to an inverse power law with the depth of the anomalous body. Furthermore large physical-property contrasts frequently occur in the surface material, making the detection and interpretation of subsurface conditions difficult.

The mining structures controlling ore deposition are small, measuring the order of feet to hundreds of feet, and are manifold in number. The direct detection of ore is seldom possible.

A more accurate assessing of the limitations and scope of existing methods to know the extent of their application, more rigorous mathematical interpretation procedures, development of methods for the detection of scattered sulphides, and drill-hole and underground exploration techniques are suggested as worthy of study.

PART A

I. INTRODUCTION

The purpose of this article is to present the main problems of mining geophysical exploration and to outline the difficulties of application and the limitations of the methods applied. The contrasting factors in mining and petroleum exploration are listed. Developments which may reduce the uncertainty and increase the applicability of geophysical procedures to mining exploration are discussed. The subject matter has been simplified and generalized as much as possible so that the main factors can be directly presented in a nontechnical fashion.

II. COMPARATIVE FACTORS IN PETROLEUM AND MINING EXPLORATION

Petroleum Exploration

1. The targets are large, usually miles in dimension, for example, the new Leduc field in Alberta is 10,000 acres to date.

Mining Exploration

1. The targets are small, tens to hundreds of feet in dimensions. The Goldfield, Nevada, gold veins are approximately 5 feet wide, and branch flatly off the east-dipping Columbia Mountain fault represented by 2 feet of gouge. The rich Tsumeb is a steeply dipping primary lead-zinc ore body not over 30 feet wide. A circle 500 feet in radius covers most primary and re-

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Petroleum Exploration cont'd.	*Mining Exploration cont'd.*
	placements sulphide bodies, for example, the United Verde. The only ore bodies comparable in size to oil and gas structures are the porphyry coppers, for example, Bingham and some lead mantos deposits.
2. The host rock and formations are consistent over wide areas.	2. A wide variety of host rocks and formations may occur over limited distances. In the Noranda-Quebec area within a range of 2 miles, gold mines are located in andesites (Donalda), diorites (Senator), granite (Powell).
3. Possible structures controlling occurrence are limited in number, e.g. flexure, fault, unconformity, pinched-out beds, reef, and generally tend to recur over a wide area, with odds only 10 to 1 against pay at structurally defined locations, for example, the sandstone fields of East Texas and the Gulf Coast.	3. A great range of possible structural and geological ore depositional controls exist with odds of 100 to 1 or more against pay at any geophysically or geologically defined location.[1] Again in the Noranda area,[2] Quebec, within a radius of 10 miles, ore deposition structural controls include a faulted, tightly folded syncline, Noranda; a replaceable breccia at the apex of a flat-lying anticline, Quemont and Amulet; fractures or faults flat-dipping to the north at Senator, to the south at Donalda; embayments in an intrusive syenite-andesite contact, Aldermac; a steeply dipping, broad, silicified regional shear, Lake Wasa.
4. Test exploratory drilling is expensive on a per-foot basis ($8.50 per foot for 5,200–5,500 foot wells in the Leduc area). Actually, a portion of these costs can be considered in the development category.	4. Test exploratory drilling is relatively inexpensive on a per-foot basis ($2.00–$8.00), but is usually not carried beyond an economic limit of 1,000 feet (see 5).

[1] W. H. Newhouse, "Ore Deposits as Related to Structural Features" (Princeton University Press, 1942), 26–28.
[2] M. E. Wilson, "Noranda District, Quebec," *Geol. Surv. of Canada, Memoir 229* (1941).

Petroleum Exploration cont'd.	*Mining Exploration cont'd.*
5. The development work per test well to obtain crude is relatively inexpensive. Fifty thousand dollars covers casing, cementing and capping per well in the Leduc area.	5. The development work to prove and obtain commercial ore is relatively costly, involving considerable surface drilling, underground work and milling. Costs may range from 1 million dollars for a small Canadian gold mine to 50 million dollars, for example, the San Manuel porphyry copper.
6. Out of a roughly 4-billion dollar annual crude product value, U. S. oil companies spend over 100 million dollars, or 3 percent, on geophysical exploration.	6. Out of a 300-million dollar annual metal value, Canadian companies, for example, spend 5–6 million dollars, or 2 percent, on exploration, largely on shallow drilling and the rest on prospecting and geology, and five hundred thousand to one million dollars on geophysics.

In oil exploration lack of surface or shallow occurrences and expensive test drilling has led to the intensive study of geophysical techniques. The nature of the problem (2 and 3) has admitted the development of a method (seismic) with a high certainty factor and the application of an essentially standardized procedure.

Because near-surface deposits were still to be found, and because exploratory drilling was relatively inexpensive with a high certainty factor, whereas the geophysical techniques applied had marked depth limitations and high uncertainty factors (see 2 and 3), mining exploration has relied essentially on geology and drilling, and has expanded successively to those areas where this exploration technique can still be economically applied, as witness the recent American exploratory commitments in North and South Africa, Australia, and South America.

Today mining exploration, quite as exploration-minded as the oil industry (see 6), is in the position where much of the exposed crustal portions of the earth have been examined, where the demand for metals is high and apt to continue, and yet where perhaps the tools fail for the economic exploration of many of the possible mineral areas more deeply covered with drift, alluvium and later formations. At the same time there exists the incentive to create acceptable substitutes for many of the duties of metal. Hence, the problem of the economic exploration of possible mineral-bearing areas is a vital one.

The interest shown by many petroleum geophysicists is warmly welcomed, and it is sincerely felt that their technical and scientific background can contribute much.

III. A COMPARISON OF PETROLEUM AND MINING GEOPHYSICS

Petroleum Geophysics	*Mining Geophysics*
1. In petroleum geophysical exploration, none of the procedures are direct, that is petroleum is never directly located, nor is this theoretically possible except by soil and gas analysis, which in other respects is seriously limited. Thus, geophysical work is directed toward providing geologic and structural evidence for geologic deduction.	1. Likewise in mining, it is seldom possible to directly detect ore unequivocally, although it is not infrequently possible by association as, for example, the association of magnetite and pyrrhotite with nickel in Venezuela and Sudbury, respectively. Similarly, to date, most mining geophysical work has been directed toward providing geologic and structural information so that from geologic association possible ore locations can be deduced, for example, the tracing of the Rand extension by the magnetic slates, one of the conformable formations.[3]
2. The seismic method, generally applied, has no serious depth limitation, since the error in time measurements is independent of depth to reflecting or refracting horizon.	2. The force-field or potential methods, generally applied (see IV), have serious depth limitations, the expected anomaly varying as some inverse power of the distance to the body. For most cases, depending on scale, this limits measurable anomalies to, at most, a few hundreds of feet from the causative body.
3. Surface features usually admit sufficiently accurate evaluation in the unglaciated, flat-lying conditions of many of the oil areas but occasionally give trouble—for example, the seismic ghost structures due to bedrock topographic elevations and depressions in Southern Alberta, and the difficulties arising from irregular drift for seismic and gravity work in Michigan and Pennsylvania.	3. The general surface and bedrock topographic features with the physical property and elevational differences involved frequently give rise to large anomalies difficult to accurately evaluate, for example, the bedrock topography in gravity work; surface swamps, and outcrops in self-potential, resistivity and electromagnetic work; overlying Tertiary volcanics in magnetic work.

[3] C. A. Heiland, *Geophysical Exploration* (1940), 420.

Petroleum Geophysics cont'd.	*Mining Geophysics cont'd.*
4. The limited number of structural types of occurrence, the close correlation between structure and occurrence, the lateral homogeneity of the formations, and the large areal extent of the target permit relatively certain interpretation of seismic data and good geologic control.	4. The great rock variety usually present at a metal ore deposit, the irregularity of formational extent and contacts, and the overlapping and not infrequently inconsistent physical property ranges for each rock material make mathematical-physical interpretation and the determination of the seat of the anomalies uncertain. The uncertain correlation of geology and structure to ore and the geologic possibilities admittedly present decrease the certainty of interpretation as a directive to possible ore. Hence, the uncertainty factor in mining geophysics is frequently very high.
5. Where seismic procedures are applicable, the absence of structure is also recorded with a high degree of certainty.	5. The absence of anomalies attributable to bedrock conditions in many cases does not necessarily eliminate the possibility of ore or an acceptable structural condition, for example, self-potential and geochemical surveys.
6. Seismic procedures are applicable to 50 percent of the possible oil areas.	6. Because of 2, 3, and 4, there are large areas of geologic possibility where, to date, geophysical procedures have not been economically applicable, for example, much of the southwestern United States lake bed area.
7. Well surveying methods, utilizing self-potential, resistivity, radioactive, and thermal measurements, record conditions largely confined to the immediate vicinity of the well.	7. Most mining geophysical procedures are readily applicable underground in drifts and drill holes where factor 3 is largely eliminated. Most of the trials have attempted to reach as great a distance as possible from the hole or drift (see 2).
8. Because of 4, it has been possible to use standardized procedures admitting rapid areal coverage.	8. Because of 4, mining geophysical work will likely be on an "artcraft" basis with procedures, scale relations,

Petroleum Geophysics cont'd.	*Mining Geophysics cont'd.*
	and detail selected appropriate for the problem.
9. Air photographs are useful in geological mapping and planning work. Airborne magnetic methods will yield essentially basement anomalies.	9. Airborne work, magnetic and other methods, and geology and alteration from air photos should have more application to mining exploration than to oil, since they provide geologic information more closely related to the rocks and conditions associated with possible ore locations.

IV. MINING GEOPHYSICAL METHODS AND THEIR GENERAL LIMITATIONS

The following geophysical methods have been applied to mining exploration work:

1. Magnetic
2. Self-potential
3. Resistivity, ratiometer, and equipotential line
4. Electromagnetic induction
5. Gravimetric
6. Geothermal
7. Radioactive
8. Geochemical
9. Seismic

Methods 1 to 6 can be lumped together as the force-field or potential group in that they are all dependent on the action of a natural or artificially created force field on bodies of contrasting physical property. Depending on the procedure the resultant potential, field component, or field gradient can be measured.* This force-field group of methods have been the ones essentially applied to mining.

The main limitations to geophysical methods applied to mining exploration arise from the following causes: (a) The lack of sufficient physical property contrast on the part of the body or condition sought; (2) the decrease of anomaly with distance to the causative body; (3) the marked anomalies frequently arising from surface features; (4) the uncertainty of interpretation as measured by the actual "ore-finding" or "ore-elimination" information provided.

All geophysical methods in application fundamentally depend on the presence of bodies of contrasting physical property. From the observed changes in the measured physical quantity, the attempt is made to derive a configuration of surface and subsurface bodies and to deduce the associated physical-property

* Obviously then, many geophysical techniques involve a change in procedure without the determination of a fundamentally different physical property characteristic.

differences. Geologic terms are then assigned to the derived bodies. This is the procedure of interpretation, the first step of which is mathematical-physical, the second, geologic.

Any geophysical method may be limited by lack of physical-property contrasts between the ore or formation sought and its surroundings. Apart from any depth, size or surface-feature limitations, the direct detection of mineralization or ore will depend on the presence of a physical-property contrast which frequently is lacking. Thus increased porosity or fracturing may eliminate a density difference, as for certain of the Labrador hematite bodies, the Missouri and Morocco mantos leads, etc. The absence of pyrrhotite may wipe out the expected magnetic anomaly over primary or massive replacement sulphides, as for certain of the sulphide lenses in the Jerome area. A high water table may inhibit the spontaneous polarization of a scattered sulphide in fractured gold-bearing quartz, as for example, the MacLeod Cockshutt gold mines, Little Long Lac area. The fact that conducting lead-zinc sulphides are not interconnected, but segregated in a nonconducting silica and siderite matrix, may remove all possible conductivity contrast for resistivity and lower-frequency electromagnetic methods, for example, Coeur D'Alene.

An exemplary consideration is Bonne Terre, Missouri, where 3–5 percent lead occurs in a flat-lying dolomitic limestone horizon. The increased density due to the lead is largely wiped out by increased porosity. Magnetic anomalies in part correlatable to basement highs which may have some association with ore deposition, are largely caused by variations in the magnetic properties of the basement. Seismic refraction work to define basement highs consistently picked out the high velocity Bonne Terre crystalline limestone. Due to the scattered nature of the sulphides, direct detection by resistivity or low-frequency electromagnetic procedures is unlikely.

It is seldom that an ore body can be or has been unequivocally detected and interpreted as such from mining geophysical work. The best chances are for large-dimensional bodies such as replacement sulphides and hematite. Most finds* have been made by drilling what were possible anomalies (Quemont,[4] East Sullivan) or by drilling a structure or formation whose relationship to a geophysically traced horizon was well established geologically, for example, the Witwatersrand extension,[5] and Steep Rock Lake.[6]

Hence most mining geophysical work is indirect and based on the tracing of formations or conditions whose relationship to possible ore locations can be deduced geologically.

* A paper on recent mineral discoveries and the events leading to discovery was read to the A.I.M.E. March, 1948 by I. R. Joraleman.

[4] T. Koulomzine and L. Brossard, "The Use of Geophysics in Prospecting for Gold and Base Metals in Canada," *Geophysics*, XII (October, 1947), 651.

[5] C. A. Heiland, *op. cit.*, 419–420.

[6] A. A. Brant, "Geophysical Work at Steeprock Lake (Ontario)," *Canadian Inst. Min. Metallurgy Trans.*, *43* (June, 1940), 274–284.

All the force-field methods are distance or depth limited, the actual anomaly varying with the dimensions of the body concerned. Thus, the scale factor becomes important, since it is really the distance or depth in terms of the dimensions of the body that is involved. Thus the 25 foot-wide, steeply dipping replaced breccia, under 75 feet of drift, which is the Falconbridge nickel ore zone, would give the same magnitude of magnetic or electromagnetic field anomaly as a 100-foot-wide zone of similar properties under 300 feet of cover. For narrower formations then, the decrease of anomaly with depth is rapid while for broader formations, gradual. Thus, it may be possible to detect broader units under considerable cover or from considerable altitude. The dimensions of most larger metal deposits, apart from porphyry coppers, are such that detection under 500 feet of cover by gravity, magnetic, electric or other force-field means marks about the extreme limit. Thus, for gravity work a 0.05-milligal overall probable error represents 3–10 million tons of 10–11 foot^3/ton sulphide ore under 500 feet of cover. The 3,000-gamma anomalies over the Quemont copper and the El Lynn Lake nickel bodies reduce to the order of 100 gamma at 500 feet elevation.

By comparison, it is seen that the small scale of many vein deposits, notably gold, and of the associated formational and structural features, introduces a shallow-depth limitation and mitigates seriously against detection even when physical property differences are present.

Hence this so-called depth or resolving-power limitation constitutes a fundamental limitation which can be pushed back only percentagewise. It seriously limits work on narrow formations or zones.

Since the surface materials such as rock, clay, sands and water, have contrasting physical properties and are nearest the recording point, it is obvious that surface features in mining geophysics frequently create large anomalies. These are difficult to accurately evaluate, for example, electrical resistivity, and in part may blanket anomalies due to subsurface causes and thereby render interpretation uncertain. Unknown bedrock topography beneath the surface drift in the Lynn Lake nickel area gives rise to gravity anomalies of the order of 0.1 milligal, that is, about the same size as the expected anomaly for a few million tons of sulphide. Elevational and outcrop features in the Flin Flon area create self-potential anomalies from a few tens to hundreds of millivolts. Good conducting wet surface areas, northern Ontario and Quebec, may cause apparent resistivity changes of 95 percent. Elevational and surface factors must be considered carefully in any electromagnetic procedure. Magnetic surface Tertiary volcanics render magnetic work impractical in the Jerome, Bingham, and Tintic areas. In many cases in Canada and the United States, anomalies, considered due to bedrock conditions and drilled, were actually the result of surface features and could have been shown to be such.

The major limitation to mining geophysical methods, however, is the uncertainty factor connected with interpretation.

In the process of interpretation, the first step is to reproduce the observed

physical data by deriving by mathematical-physical means a series of surface and subsurface bodies with associated physical properties. Theoretically, a unique solution is not possible. Actually, several configurations may reproduce the results within the range of error arising from experimental and surface conditions and mathematical approximations. The configuration selected as most consistent with the results, in view of the geologic controls, will be at best a generalization of a geologic complexity. This step can generally be adequately carried out, although too little attention has been given to a mathematical-physical analysis of results.

The second step involves assigning geologic significance to the derived configuration. It is here that the greatest difficulties arise for the rocks generally associated with a likely ore occurrence usually exhibit great variety, irregularity of extent and distribution, and frequently overlapping physical properties, so that a deduction of the possible idealized shapes and physical properties of the bodies causing an anomaly, still leaves ambiguity as to what rocks or conditions the deduced bodies represent. Also the possibility that a given anomalous condition represents a possible ore association may be very slight and yet definitely exist, thus immediately introducing a high uncertainty factor.

For example, any increased resistivity anomaly obtained while working on a lake surface, for example, Steep Rock Lake, could be due to a steeply dipping, more resistant formation such as hematite, or a bedrock topographic high. Under certain conditions the difference would be difficult to establish.

Magnetic anomalies in the Noranda area can arise from gabbro, scattered magnetite in andesites, and pyrrhotites, either scattered or associated with dense sulphides. Conceivably, the deduced bodies might all have the same approximate attitude, dimensions and susceptibility. Actual anomalies, due to the above causes occurred at Quemont, although there was some evidence for differentiation.[7]

At Lynn Lake gravity anomalies of 0.1 milligal resulted from sulphides, bedrock topography and fingers of induration adjacent to the gabbro.* Analytical means of differentiation by solving for density were applied but uncertainty still remained.

The extensive airborne magnetic work in Canada, done independently by International Nickel and Dominion Gulf, have resulted in whole series of magnetic anomalies that may be due to a number of causes, for example scattered magnetite in tuffs and flows, basic intrusive plugs, scattered pyrrhotites and perhaps a nickeliferous sulphide body. From the air at 500-feet elevation it will be impossible to establish the dimensions and susceptibilities of bodies under approximately 1,000-foot size. It is obvious that, even with good geologic control, considerable uncertainty of interpretation will exist for any of the approximately 1,000-foot sized anomalies. And yet, a 1,000-foot circle covers, and to spare, the sub-outcrops of Noranda, Quemont, Hudson Bay Mining and Smelting and the El ore body at Lynn Lake.

[7] T. Koulomzine and L. Brossard, *loc. cit.*

* From recent gravity results at Lynn Lake for Sherritt Gordon Mines Limited.

In addition to the uncertainty factor of the geophysical interpretation there is also the associated geologic uncertainty factor measured by the probability that a geologically recommended set of conditions will lead to discovery. The combined over-all uncertainty factor of geophysical results to geologic data, to geologic deductions, to localization of ore, is very high, several hundred to one against. Economically this has done much to restrict mining geophysical field work and research.

Similarly the uncertainty factor in geophysically eliminating ore possibilities or providing data therefore may be high.

To my mind, this uncertainty factor is the most serious limitation to mining geophysics and mining exploration in general. It is a challenge to both geophysicists and geologists, to the former for more scientifically based, reliable interpretative techniques , and to the latter for evolving the means for a narrower, more reliable localization of likely ore conditions.

In short then, the essential limitations in geophysical mining exploration are the indirectness of the methods in most cases, the factors of scale and associated depth limitation, the effects of surface features, and the over-all uncertainty of interpretation in terms of the localization of, or the elimination of, possible ore occurrences.

Each mining geophysical survey is usually a specialized problem in itself and is likely to remain so. Geophysical exploration in the petroleum and mining fields is almost comparable to highly developed and skilled mass production on the one hand and hand craft on the other.

V. SUGGESTED DEVELOPMENTS IN MINING GEOPHYSICS

Any developments suggested should be such as to reduce the aforementioned limitations.

(1) In over-all application, what geophysical methods *cannot* do is quite as important as what they can do. Little progress will be made until the limitations and shortcomings are bluntly stated (see part II) and the whyfor realized. Too many mining geophysicists have been unwilling to admit the limitations. Too few engineers and geologists realize them. A realization of the shortcomings is the first step toward a healthy development.

(2) A better engineering and scientific approach is demanded. For example, if the approximate geologic conditions are known, and if the rock properties can be measured in a laboratory, or otherwise determined, it should be possible to compute the anomalies likely to result by any geophysical method. This should permit a scientifically based decision as to what method or methods, if any, warrant application. The "try-everything" philosophy is extravagant, poor engineering and an admission of inadequacy.

(3) Improved and greater use of mathematical-physical procedures should be made for the analysis of results, the quantitative evaluation of surface features, etc. Much is yet to be done in the way of direct curve analysis, the establishment of type curves and the use of computation charts. Comprehensive model tests

should be used to check theory and to evaluate certain factors empirically, such as the electrification of tabular bodies, which cannot be handled mathematically. It should be realized that any sound interpretation has to satisfy all the physical field results as well as the geologic controls.

(4) The development of techniques permitting geophysical measurements in underground workings and diamond drill holes is an important item. This would, in part, beat the depth limitation and greatly aid development work. Actually, magnetic, self-potential, resistivity, electromagnetic, radioactive, geothermal and seismic methods with little modification can be applied from EX diamond drill holes of $1\frac{3}{4}$-inch diameter.

(5) Airborne magnetic and other airborne methods in process of development, as well as the extended uses of airphotos, provide the data for rapidly obtaining a regional geologic picture and singling out areas of geological and geophysical interest.

(6) Despite the fact that most ore deposits represent the concentration of an "anomalous" material, implying perhaps some characteristic physical property, no generally diagnostic recordable physical-property or properties have been found. Any approach to a fundamentally new method should start from here, basing itself on an investigation of the physical-property characteristics in the widest sense. Thus, for example, though scattered sulphides represent deposits in "mantos" and "porphyry" form, and are associated with perhaps 90 percent of all mineral deposits, no method to date exists for detecting them with reasonable certainty. There is room then for fundamentally new methods.

(7) Fundamental geophysical and geologic research is needed to the end of establishing means for the narrower and more certain localization of possible ore areas. This should involve geophysically basic physical-property determinations on rocks from mining areas, regional magnetic, gravity and radioactive studies, mathematical formulation, model studies, etc.

PART B

I. BASIC SIMILARITIES OF THE FORCE-FIELD GROUP OF METHODS

The force-field group of methods, since they are all based on the action of a natural or artificial field, should admit similarity of expression.

Thus the vertical-field-component anomaly Z' at any point (0,0) in the xz-plane for a sphere magnetized by a field F in the xz-plane at direction i to the x-axis is given by

$$Z' = \frac{(K_1 - K_0)}{1 + 4/3\pi(K_1 - K_0)} 4/3\pi a^3 \left[F \sin i \left(\frac{2z^2 - x^2}{r^5} \right) + F \cos i \left(\frac{3xz}{r^5} \right) \right], \qquad (1)^8$$

[8] H. Haalck, *Handbuch der Experimental Physik*, XXV, Pt. 3 (1930), 332.

where K_1, K_0 are the susceptibilities of the sphere and its surroundings, a is the radius of the sphere, x, z are the coordinants of the center of the sphere with respect to the observation point (0,0), and z is vertically downward.

The amplitude of the vertical secondary field component F_z' due to the excitation of a conducting sphere by a horizontal electromagnetic field F_x is given by

$$F_z' = C \frac{a^3}{2} F_x \cdot \frac{3xz}{r^5}, \qquad (2)^9$$

where C is an intensity coefficient having a value between 0 and 1.

The increase or decrease in voltage drop, such as would be determined by a resistivity factor, is actually equal to the electric-field-component anomaly in the direction of the pickup stakes multiplied by the interval between the stakes. For a sphere electrified by a horizontal uniform field F_x, the anomalous voltage drop ΔV detected on surface divided by the separation of the pickup electrodes in the x direction ΔX is given by

$$\frac{\Delta V}{\Delta X} = - \frac{(\sigma_1 - \sigma_0)}{\sigma_1 + 2\sigma_0} a^3 \cdot F_x \cdot \frac{2x^2 - z^2}{r^5}, \qquad (3)^{10,11}$$

where σ_1 and σ_0 are the conductivities of the sphere and its surroundings.

The above equation would equally well express the anomalous temperature gradient resulting from a sphere of thermal conductivity σ_1, surrounded by rock of thermal conductivity σ_0 in which the normal temperature gradient was F_x.

The spontaneous-polarization potential V at an observation point (0,0) arising from a sphere with center at x, z polarized by oxidation currents, in the xz-plane at a direction i to the z-axis, becomes, where F is the equivalent electrifying field,

$$V = a^3 \left(F \cos i \cdot \frac{z}{r^3} - F \sin i \cdot \frac{x}{r^3} \right). \qquad (4)$$

The gravity anomaly ϕ' at (0, 0) for a sphere at x, z is

$$\phi' = (\rho_1 - \rho_0) 4/3\pi a^3 \cdot G \cdot z/r^3, \qquad (5)$$

and the anomalous gravity gradient in direction x is

$$\frac{\partial \phi'}{\partial x} = (\rho_1 - \rho_0) 4/3\pi a^3 G \cdot 3xz/r^5, \qquad (6)$$

where ρ_1, ρ_0 are the density of the sphere and its surroundings and G is the universal gravitational constant.

[9] L. B. Slichter, "Observed and Theoretical Electromagnetic Model Response of Conducting Spheres," *Trans. AIME Geophysical Prospecting* (1932), 448.

[10] J. H. Jeans, *Electricity and Magnetism* (1925), 228.

[11] J. A. Stratton, *Electromagnetic Theory* (1941), 204.

Equations (1), (2) and (3) express anomalous forces which can be considered as the result of the acting field producing dipolar effects. The dimensions are the same as for the gradient of unipolar effects (equation (6)).

Equation (4) expresses the case of the anomalous potential, rather than the anomalous force, of a dipolar effect. The dimensions here are equal to those of the force for unipolar effects (equation (5)).

Defining

$$W \quad \text{as} \quad \iiint \frac{1}{r}\, dxdydz$$

over the limits of the body of contrasting physical property,

$$W_x \quad \text{as} \quad \iiint \frac{x}{r^3}\, dxdydz,$$

and similarly for y and z,

$$W_{xz} \quad \text{as} \quad \iiint \frac{3xz}{r^5}\, dxdydz,$$

and

$$W_{zz} \quad \text{as} \quad \iiint \frac{2z^2 - y^2 - x^2}{r^5}\, dxdydz,$$

we see that the anomalous potential U' due to a force field creating dipolar effects is given by

$$U' = F_x P_x(-W_x) + F_y P_y(-W_y) + F_z P_z(-W_z). \tag{7}$$

The anomalous force or field component F_x' in the direction x is

$$F_x' = F_x P_z W_{xz} + F_y P_y W_{xy} + F_z P_z W_{zz}, \tag{8}$$

where $F_{x,y,z}$ are the components of the normal or acting force field, and $P_{x,y,z}$ are the physical-property functions involving the property difference between the body and its surroundings in the x, y, and z-directions. The physical-property functions can be mathematically determined if the body is a sphere (for example equations (1) and (3)), ellipsoid or cylinder. For tabular bodies, it can be approximated if the property difference to the surroundings is small, or evaluated from scale-model tests.

From the above it is apparent that equation (7) also represents the general expression for the anomalous force or field when the acting field creates unipolar effects. For unipolar effects the anomalous potential becomes the product FPW.

For steeply dipping tabular bodies which extend to depth and have considerable strike length, as in the Canadian pre-Cambrian:

$$W_{zz} = \log_e (r_2/r_1),$$
$$W_{zz} = (\phi_1 - \phi_2).$$

The vertical magnetic-component field anomaly across such a body, disregarding demagnetizing effects since $(K_1 - K_0)$ is small, becomes from equation (8)

$$Z' = (K_1 - K_0)[F \cos i \cdot \log (r_2/r_1) + F \sin i \cdot (\phi_1 - \phi_2)].$$

The amplitude of the vertical secondary-field component arising from the

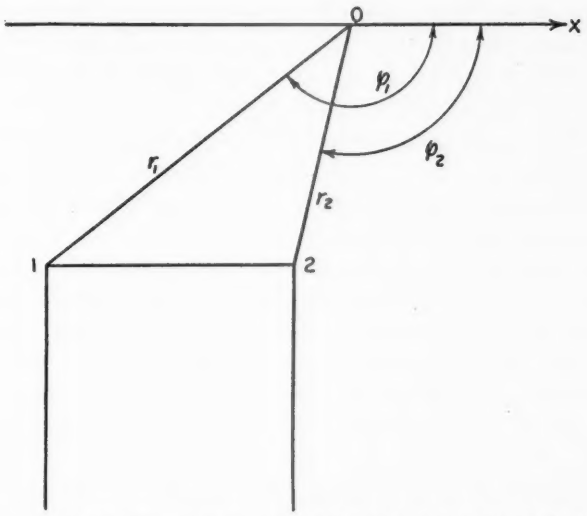

FIG. 1. Geometrical elements for computing the field of a vertical tabular body.

action of a horizontal electromagnetic field of strength F_x will be, again from equation (8),

$$F_z = C \cdot F_x \log_e (r_2/r_1),$$

where C is a coupling or intensity coefficient involving the body's conductivity, its width, and the frequency.

The voltage drop between two potential pickup electrodes distance Δx apart where a horizontal field of F_x is present at the tabular body, as a result of the current electrode arrangement, is

$$\Delta V = \Delta x\{F_x + F_x P_x W_{zz}\} = \Delta x\{F_x + F_x P_x(\phi_2 - \phi_1)\},$$

were P_x is a function of the conductivity of the body, its surroundings and its dimensions. In P_x will be incorporated the de-electrification coefficient.

Fundamentally the anomalies to be expected for the force-field group of methods lead to parallel expressions, similar type curves, and the use of similar charts for the evaluation of irregular-shaped-body effects, at least as far as the

W-, ∂W- and $\partial^2 W$-expressions are concerned. For tabular and irregular bodies, the P-function can only be derived empirically from model tests which should permit curves to be drawn up so that P can be established approximately, once the shape and attitude of the body have been assumed or established.

II. DISCUSSION OF MINING GEOPHYSICAL METHODS

The limitations and difficulties of application of each of the generally practiced mining geophysical methods are discussed below.

Self-Potential.—For spontaneous-polarization methods to be effective, oxidation must be going on. Thus, sulphides may be present, but unless undergoing oxidation, no anomalous potential indications will result. Beneath the permanent water table, within the permafrost layer, and under frozen ground, oxidation appears so inhibited that anomalies associated with sulphides do not result; for example a sulphide core drawn from beneath the lake at Quemont showed no oxidation. Sulphides and arsenides at MacLeod Cockshutt gold mines gave 200 millivolts self-potential anomaly under shallow sand and 100 feet away under shallow muskeg (permanent water table) did not react.

In addition, since an atmospheric potential gradient of roughly 100 volts per meter is present, elevational differences give rise to marked self-potential anomalies, particularly where the surface material is of poor conductivity, as for example, where outcrops are present. Thus, self-potential lows of tens to several hundred millivolts can be obtained over drift and rock ridges and at the base and apex of slopes, for example, work by McIntyre mines in Warden Township, Ontario.

Earth currents result in self-potential anomalies occurring with changes in conductivity as at rock contacts, for example, Rhyolite, Nevada, at the contacts of different surface materials, and above bedrock ridges or valleys if the drift is shallow.

In many cases, these anomalies can be recognized by their location relative to known elevation, surface and geologic features, and by their characteristic shape. Nevertheless, in a series of anomalies of 20–50 millivolts amplitude, it is impossible to determine with certainty which to ascribe to sulphide oxidation.

Thus, the self-potential method, while perhaps giving a clue to the location of sulphides, does not eliminate their presence if no anomalous potentials result and may not, and frequently does not, give an unequivocal indication of sulphides even when anomalies are present. Hence the uncertainty factor is high. It is important that self-potential work may indicate scattered sulphides, the ability to do which is one of the most marked shortcomings of mining geophysical methods.

Self-potential methods may be applied underground, using saturated copper sulphate pads to contact the rock, and in drill holes, e.g. dry oxidation gave rise to anomalies underground in the East Tintic area. Most mines create a dimple depression in the water table thereby initiating oxidation in areas until recently beneath the water table.

Since in most self-potential work a voltage difference is measured, this will fall off as the $\partial^2 W$-function for the body undergoing oxidation (see Part B, I) while the recorded potential will decrease according to ∂W. Thus, a steep sulphide zone 20 feet wide, giving a self-potential anomaly of 100 millivolts under 50 feet of drift, theoretically will give approximately 30 millivolts under 200 feet of drift. A flat-lying lens of ore at 100-foot depth, 20 feet thick and 200 feet wide, with considerable length, would give a self-potential of 60 millivolts with oxidation proceeding at the same rate as for the above body.

Despite the fact that theoretically the recorded self-potential minimum falls off as ∂W and therefore more slowly than recorded magnetic and resistivity anomalies, none except shallow bodies have ever been inferred from self-potential work, perhaps because the actual electrified or polarized part of the body is essentially the oxidizing portion.

The "E" and "G" Noranda ore bodies were indicated by S. F. Kelly during development work at Noranda. Moulton Hill, a small copper ore body near Sherbrooke, Quebec, was localized at shallow depth by A. R. Clarke, using self-potential and resistivity methods without the benefit of nearby ore or outcrops.

Self-potential work is limited by uncertainty as to cause of anomalies, uncertainty as to elimination of sulphides and poor resolving power. It has the advantage of being able, with the uncertainty factor involved, to detect scattered sulphides.

Resistivity.—The resistivity group of methods should actually include all equipotential-line, voltage-drop and voltage-drop-ratio methods in that in all these, an artificial electrifying field is created by the use of grounded electrodes and departures from the normal field due to the electrification of bodies of contrasting conductivity are measured. Hence, though the procedures differ, they will all be encompassed by the same fundamental limitations of distance or depth, that is, resolving power, the effect of surface features and the non-uniformity of rock conductivities.

Other factors being equal, the most marked anomalous-field, that is, voltage-drop, effects should take place for a lens or vein-like body of contrasting conductivity when it is electrified parallel to its length. This results in the equipotential-line technique, for the normal current distribution has been altered by the presence of the body.

This technique has been applied by H. F. Lundberg in Sweden and in Newfoundland at Buchans.[12]

For cross sectioning a series of steeply dipping formations a resistivity technique is generally applied with the current density (and normal electrifying field) kept constant across each formation. The voltage drops or voltage-drop ratios recorded can be considered the resultants of the normal electrifying field and the anomalous fields due to the electrification of the bodies of contrasting conduc-

[12] C. A. Heiland, *op. cit.*, pp. 704–705.

tivity (see Part B, I). The actual disposition of the formations with the narrow or width dimension perpendicular to the electrifying field, admits large de-electrifying factors. The result is that small conductivity contrasts produce relatively large voltage-drop anomalies, i.e. this procedure is sensitive to small conductivity contrasts.

Since voltage drop, voltage-drop ratio and the spacing of equipotential lines are all dependent on voltage drops, the anomalies as regards resolving power or depth limitation will involve W_{xx}, or a similar factor to that for electromagnetic, magnetic and gravity-gradient methods.

The main difficulty in applying resistivity methods in areas, such as the Canadian shield, is the marked effect of surface features. Rocks of resistivity of about 10^6 ohm-cms, clays and gravels of 5×10^4 ohm-cms, lake waters of 10^4 ohm-cms and swamps and muskegs of 2×10^3 ohm-cms are all present and form irregular bodies embedded in the prevailing rock medium. Thus, a muskeg 50 feet deep and 300 feet across in an area of shallow drift will reduce the apparent resistivity from perhaps 250,000 ohm-cms to 10,000 ohm-cms. A draw 50 feet wide and 20 feet deep on the bedrock underneath an average 50 feet of drift may reduce the resistivity from 100,000 ohm-cms to 75,000 ohm-cms, while a mineralized shear of specific resistivity 2×10^4 ohm-cms and 20 feet wide will reduce the resistivity only to 65,000 ohm-cms. A sulphide mineralized zone 50 feet wide and of resistivity 100 ohm-cms if underneath the first-mentioned muskeg, will reduce the resistivity locally only from 10,000 ohm-cms to 8,000 ohm-cms, a range of values that readily occur within the muskeg itself by deepening it 15 feet.

Thus, it is seen that the effects of draws and bedrock depressions in the Canadian shield can give anomalies similar to mineralized shears and covered sulphides. Also muskegs reduce and, to a great extent, wash out the anomaly to be expected over a well-mineralized area. The changes in resistivity at muskeg margins are greater than anything to be expected over most shallow sulphide zones.

No adequate method to date has been worked out either to evaluate or eliminate the effects of such surface features. A computational approach suffers from the difficulty of evaluating the de-electrification factors for the bodies concerned. An experimental approach such as by Kihlstedt[13] applies only to special surface-feature cases and breaks down where the surface resistivity changes markedly at a steep face. The mean-curve ratiometer procedures for deriving conducting zones can be shown also theoretically and practically to result in a variety of mean curves across a given body depending on the position of the body relative to the near-current electrodes on the going and coming traverses. In fact, in Canada at least, the conducting effects of surface features have frequently been interpreted erroneously as bedrock conditions.

In much of the western and southwestern United States, the surface conditions

[13] F. H. Kihlstedt, "Electrical Methods in Prospecting for Gold," *Trans. AIME Geophysical Prospecting* (1934), 62–74.

are relatively uniform with long slopes and dry alluvial and lake-bed cover. The difficulty here is that for the size of many lode deposits detection beneath more than tens of feet of cover is not possible. Moreover, dry oxidation has frequently converted conducting sulphides to nonconducting sulphates. Ore horizons also are frequently made up of sulphides in separated aggregates surrounded by insulating carbonate or silicate, so that a poor conductor results for all lower frequencies, for example, Coeur d'Alene dry belt.[14]

In addition certain shales even in the dry state are excellent conductors (resistivity 10,000 ohm-cms or less).

In short, a sulphide ore may be difficult to detect simply because the ore shoot is narrow and steeply dipping, and the conducting ore particles segregated or oxidized. Occasionally also conducting horizons are present, giving a response equivalent to an ore zone. Similar difficulties have been encountered in prospecting by resistivity methods for more resistant silicified areas.

Resistivity methods can be applied underground and in drill holes. Since the effects of surface features are absent, this looks like one of the more helpful applications. Again, any anticipated mineral conductor must be interconnected. Theoretically also it will scarcely be possible underground to indicate a conductor at a greater distance away than its average cross-sectional dimension. Formations of high conductivity, for example, some shales and pyritiferous limestones, segregated conductors, as well as dry oxidation as aforementioned, will provide uncertainties.

Successful examples of resistivity application are the indication of a silicified area at the sediment-volcanic contact beneath about 50 feet of drift at the Broulon Porcupine mines, by S. F. Kelly, giving a lead to the eventual ore body; the tracing of the Steep Rock hematite "A" ore body beneath 100–200 feet of water at a magnetically localized tuff-limestone contact after drill holes had established the S. E. ore tip and the indication and statement of more resistant hematite at the central "B" ore body area.[15] Underground resistivity work in drifts at the Britannia mine, B. C., by the H. F. Lundberg Company, indicated a nearby conductor which was developed as part of the Number-8 ore body.

Thus, numerous conditions are present which limit the applicability of resistivity work and render interpretation uncertain. These are: the limited resolving power in view of the scale of many ore zones, the factors affecting the actual conductivity of a zone, and the range of conductivities present both within the rocks and surface materials.

Depth of drift or depth to bedrock determinations work well in the Canadian pre-Cambrian where the drift is generally 100 feet or less and the underlying rock is of high resistivity. Here again absolute accuracy decreases with depth.

[14] F. L. Ransome and F. C. Calkins, "The Geology and Ore Deposits of the Coeur d'Alene District, Idaho," *USGS Prof. Paper No. 62* (1908).

[15] A. A. Brant, *loc. cit.*

Lack of a marked resistivity contrast at the horizon sought can render interpretation uncertain.

Electromagnetic Methods.—Low-frequency (1,000 cycle or less) electromagnetic procedures, using both vertical primary coils and horizontal primary loops, have been applied to mining exploration in Canada, Australia, and the United States. In all cases of application, the attempt has been made to detect a secondary field resulting from the energizing of some subsurface conductor.

The secondary field as seen from Part B, I, is a function of the primary field at the body, its intensity coefficient which lies between 0 and 1 and a $\partial^2 W$-factor for the body in question. The actual intensity coefficient depends on the size of the body, its conductivity and the frequency employed. Poorer conducting bodies (1,000 ohm-cms) of considerable size (hundreds of feet) may have intensity coefficients near unity, as well as smaller bodies (tens of feet) of high conductivity (1–10 ohm-cms).

Thus, in Canada the intensive application of the vertical-coil procedures at Lynn Lake, indicated conductors have included broad shears* and graphitic zones as well as interconnected sulphides, it being impossible to differentiate widths once the depth to the body becomes at least half the width. Lake and muskeg margins, as predicted by theory, have all given effects.

Work in Australia has shown that anomalous conductors may result from high-conducting ground water in shears and fracture zones.†

The method has recently been tried on the deliquescent gouge-filled Goldfield, Nevada, fault zone with small anomalies resulting.

Again numerous conditions result in anomalous effects similar to actual ore-conducting zones so that a considerable uncertainty factor is present here also. The advantage at lower frequencies is the relatively high intensity factor of the extremely good conductors, so that in contrast to the resistivity methods, this method is not sensitive to smaller changes in conductivity.

The resolving power is determined by the $\partial^2 W$-factor. Therefore, the anomaly for a spherical body falls off as the cube of the distance to the center. The effect of a steeply dipping, tabular conducting formation falls off as log (r_2/r_1) (See Part B, I) for the vertical secondary-field component used in detection with the vertical-coil primary.

Thus a 25-foot-wide vertically dipping conductor of replacement nickel-bearing sulphides, such as Falconbridge at 400-foot depth, would give a vertical secondary-field component about 3 percent of the horizontal primary field. This is just at the limit of detectability under most conditions and likely indistinguishable against the changes (3 percent) due to surface features of somewhat contrasting properties.

Elevational effects can come in strongly here as the direction and magnitude of the primary field is a function of the altitude of the observation point.

* Exploration work by Sherritt Gordon mines.

† Letter from P. C. Benedict of the Zinc Corporation and Newmont Mining Corp.

Horizontal-loop methods have been confined to areas of flat-lying formations. The practice and theory have been extensively investigated by Hedström and others.[16] In early application in Canada and Australia, flat-lying conductors, such as surface swamp and muskeg in Canada and saturated subsurface clay lenses in Australia, became highly energized and gave marked anomalies.

Neither procedure can locate scattered sulphides which are an important lead in many areas, for example, West Tintic, Tri-State, Sidi Amar, etc.

Electromagnetic methods applying higher frequencies of 50,000 cycles-per-second and over, approaching the range which may energize scattered sulphides, are also in the range of frequencies which energize small bodies such as graphitic slips, water-filled fractures, etc., so that the uncertainty of the source of the recorded anomaly becomes high. Hence such frequencies should be attempted only in dry areas of relatively massive, poor conducting rock.

Electromagnetic techniques may be applied underground and, with some modification, in drill holes, although it will be found that frequencies of 20,000 cycles and up will usually thoroughly energize the water pipes, electric cable, etc.

Low-frequency, vertical-coil methods in connection with magnetic work have found two ore bodies for Falconbridge* in the Sudbury nickel area (drift 100 feet or less) and have been used extensively in the Lynn Lake nickel area. A higher-frequency procedure is reputed to have guided leasers a few years ago to a find of shallow ore at Tombstone.†

Magnetic Methods.—Magnetic methods have been more widely applied in mining work than any other geophysical tool, because they are usually less affected by surface features and because, in general, there exist broad relationships between the rock types and their magnetic properties. By contrast, in electric methods, little conductivity difference may be present between several rock types since the conductivity essentially depends on pore and fracture volume and conductivity of the filling. Thus, magnetic methods permit a generalized outlining of the rock bodies present, for geological study, deductions and guidance. To provide such geologic information has been their most important and widespread application.

In addition, some ores in their association are magnetic as, for example, the Mesabi iron, the Sudbury nickel and, to a lesser extent the Noranda copper and Consolidated Mining and Smelting lead-zinc.

Magnetic methods, just as the other force-field methods, are limited in depth or resolving power as determined by the $\partial^2 W$-factor. The Consolidated Mining and Smelting lead-zinc body dipping 30° east, and 100 feet to 150 feet wide at the surface, has an average susceptibility of $3{,}000 \times 10^{-6}$. This would result in a ver-

[16] K. Sundberg and H. Hedström, "Structural Investigations by Electromagnetic Methods," *Proceedings World Petroleum Congress*, Section B, 1 (1934), 107.

* Personal communication from Dr. C. S. Davidson.

† Personal communication from P. C. Benedict, Newmont Mining Corp.

tical magnetometer anomaly of 300 gammas at surface, but only 30 gammas at 500 feet elevation for an airborne magnetometer. Moreover, any tabular dipping formation less than 1,000 feet wide will not be interpretable as to width in an airborne record at 500 feet elevation.

Uncertainties arise essentially out of interpretative ambiguity. Many formations exhibit variable magnetic properties along and perpendicular to their strikes, for example, many of the Quebec volcanics,* the Great Bear Lake syenites.† In given areas anomalies may arise from several sources; for example, in the Quemont Copper property of 640 acres, similar-appearing anomalies arose from scattered magnetite in andesite, dipping gabbro and the Quemont ore body and environs. The ore body was not interpreted as such but merely one of several points to be drilled.

In several areas, as in the southwest United States, overlying magnetic Tertiary flows preclude effective magnetic applications. Nevertheless, the certainty of interpretation for magnetic methods is higher than for perhaps any other mining geophysical method. The information provided has geologic value and does not merely give, as by most other methods, evidence as to the presence or absence of a presumed condition.

Magnetic work is now possible by air, using a saturation-induction device (Gulf, Aero Service, etc.) from a plane, or (Lundberg) from a helicopter. Magnetic measurements are also possible underground and in drill holes.

Magnetic methods have yielded more widespread help in ore discovery than any other geophysical method. At Quemont, ore was associated with one of the anomalies due largely to an overlying black magnetic schist. At East Sullivan a magnetic anomaly, actually due to magnetite at a porphyry contact, led to drilling and a copper-gold ore discovery. High-grade nickel float found near Lynn Lake was followed by field parties for 7 years before magnetic nickel-copper ore bodies were localized using a Tiberg magnetometer of sensitivity some 100 gammas per degree.‡ Magnetic work has contributed to the developments at Sudbury, Steep Rock Lake, the Little Long Lac gold camp, the Rand Extension in Africa and elsewhere.

Gravimeter Work.—Gravimeter work is entering on a widespread test period in mining. Many ores, for example, copper and lead sulphides, hard hematite, barite, etc., have high density.

Again ores may be associated with areas of fracturing which give a gravity low,¶ for example, lead ore in zones of fracturing in limestone, South Africa. Many intrusive margins may be outlined by gravity and a better idea obtained than by magnetics as to how they extend at depth.

The limitations of the gravity method are determined by resolving power,

* Senneville and Vassan Townships, Quebec.

† Work at Great Bear Lake, Mines Department, Ottawa, 1944.

‡ Personal communication from Eldon Brown, Sherritt Gordon mines.

¶ Work by Oscar Weiss in South Africa.

the effect of surface and bedrock features and the combination of rock properties existent, for example, density, porosity, etc.

The resolving power is determined by ∂W which is a step above the magnetic resistivity and electromagnetic anomalies. Specifically a 100,000-ton lens-like sulphide body at the surface could be missed by the 0.05-milligal error factor. Similarly a 1–3 million-ton body at 500 feet depth and a 5–15 million ton at 1,000 feet could be overlooked, assuming 11 cubic feet of ore to the ton, that is, a density difference of about 0.2 to 0.5 gm/cm^3.

Bedrock topographic features rather than actual surface features cause difficulty. The interface between the overlying drift of density 1.5–2.2 gm/cm^3 and the underlying rock 2.6–3.0 gm/cm^3 is seldom a plane, so that appreciable anomalies arise over the hills and hollows of the bedrock surface. Under lakes and deep sand plains, it is difficult to check the presence of such a feature as a scarp either seismically or electrically. For many features, however, a spot-depth test should suffice.

Thus, for example, in gravity work from the ice with 100 feet of water, a silt- and clay-covered ridge 200 feet wide and 50 feet high would give much the same anomaly as a hematite or sulphide ore body—0.2–0.4 milligal.

A likely location for an ore occurrence is at the margin of an intrusive. The intrusive frequently gives rise to a fingered gravity anomaly of considerable magnitude, for example, 1 milligal for the gabbro at Lynn Lake. The presence of a sulphide ore body on or between the fingers would be extremely difficult to recognize. Thus, a gravity test across the new East Sullivan copper discovery of 5–10 million tons clearly indicated the intrusive contact, but gave no clear-cut evidence of the ore.*

The variations in density of a formation or ore are tricky. Gravity tests across several of the Labrador iron-ore bodies showed density ranges from 0.0 to 0.8 gm/cm^3 with respect to the surrounding iron formation and quartzites. One ore body actually gave a negative gravity anomaly. Tightly folded iron formations high in iron also gave positive gravity anomalies. A 4 percent lead ore scattered over a great volume, as in the Bonne Terre, Missouri area and at Sidi Amar in Morocco, should give a theoretical density difference of 0.2 gm/cm^3 and a gravity anomaly of some 1/10 milligal. Yet the density increase is largely wiped out, apparently by porosity due to vugs, slips, etc.

Gravity work provides considerable geologic information as well, since formational units give broad gravity levels. Such things as open faults and fractured areas show up well.

Gravity surveys in mining, due to the bedrock-topography difficulties and less formational differentiation, will generally be less widespread and less certain in application than magnetic work.

Geothermal Methods.—The last force-field method is the geothermal where temperature gradients correspond to the observed forces and are dependent on

* From a discussion with T. Koulomzine who arranged the work.

the thermal conductivities, dimensions and forms of the bodies present for the steady state of heat flow.

Little has been done to investigate the use of thermal-gradient measurements to ore prospecting. Dry oxidation above the water table creates considerable heat once workings are opened up. The rate at which oxidation proceeds before the rock is removed is not known nor the distance away at which any such heat might be detected in a drill hole. Abnormal temperature gradients might indicate the proximity of a late intrusive. Otherwise, temperature gradients are largely a function of the percentage of electrolyte filling of the rock, and therefore closely related to conductivity.

An application of temperature measurements is to predict the temperature to be expected at depth in a mining operation. This permits the over-all ventilation problem to be anticipated.

Radioactivity.—To date in mining work, radioactive measurements, apart from age of rock determinations, have largely been confined to prospecting for uranium, as for example the last 3 years' activity in the Great Bear Lake, and Lake Athabasca area.

Two methods have been employed, utilizing simple lightweight Geiger counters and more elegant ionization chambers,* both based on the ionization effects of gamma radiation. Background counts vary with the type of rock, topography, thickness of drift cover, and the nature of the drift, since some of the soluble radioactive products show evidence of precipitation in swamps and muskegs. The ratio of recorded to initial gamma intensity is a function of the thickness of the absorbing material and its density, and also varies inversely as the distance-squared factor of the detector from the vein integrated over the area of the vein.

It can be shown that for the portable Geiger unit of background count about 40 per minute, 4 feet of average drift would blanket out the detection of the Eldorado No. 2 vein. The increased sensitivity of the ionization chamber has practically the same limitation due to the variability of the background arising from the above-mentioned factors.

The recent, almost hundred-fold more efficient Geiger-type Pentron tubes theoretically should permit detection through 20 feet of drift. Again variability of background would give rise to evaluation difficulties.

Using a Pentron or ionization chamber, gamma-ray detection from an aircraft is possible and should indicate areas of general higher activity.

Gamma-ray intensities have also been recorded down diamond drill holes and beneath 200 feet of lake water at Great Bear Lake in 1944.

Some recent work by the Ontario Department of Mines and the Ontario Research Foundation across the Kirkland Lake gold belt indicated increased radioactivity across the ore zone followed by a low in the adjacent syenite porphyries.†

* S. A. Scherbatskoy, private report on work at Great Bear Lake, 1944.

† J. T. Wilson, Paper presented at Convention of Prospectors and Developers Association, Toronto, March, 1948.

There appears hope then that an increased knowledge of regional radioactivities may provide some evidences as to ore deposition and association. Such studies seem closely related to those of alteration proceeding in the United States.*

Geochemical Methods.—These methods depend on the microanalysis of carefully selected parallel samples of soil, humus, rock debris, plant parts, or ground waters for abnormal traces of given elements, for example, Cu, Zn, Pb, Au, Be, etc. Analyses may take the form of vapor-arc spectra and densitometer measurements, chemical analyses, colorimetric tests, solid residue content, radioactivity, etc., depending on the nature of the problem and the material sought.

Any ore admitting geochemical detection must come to form part of the soil or a constituent of the ground waters. It is obvious then that the ore must have been within reach of rock decrepitating forces or of ground waters subject to surface capillarity or easy runoff. In short, the ore surface must be under shallow cover and possess a suboutcrop. Deposits covered by rock are unlikely to be found. Deep drift will prove a major difficulty, considerable soil transport a complication.

The most hopeful areas appear to be those where the rock has broken down in situ and where surface transport has been limited. Certain areas of Australia, Africa and southwestern United States conform to these conditions. It is also interesting to note that in central Labrador and the Northwest Territories, glacial erosion has been deep and much of the present drift is in place or has been transported only a short distance southerly.

Other difficulties, as in oil and gas soil analyses, are that small near sources will give indications comparable to large, more distant sources and that the absence of indications does not eliminate the presence of ore even at suboutcrop level.

Geochemical analysis has the advantage that it is direct, indicating the actual constituents. Experience will serve to delimit the applicability which is more likely to be to regional than to local exploration.

Much work on trial applications has been done in Russia, Finland, Norway, and Sweden and more recently in the United States, South Africa and Canada.[17,18,19] Of interest in Canada was an experimental survey showing the fan concentration of sample activity south of a known radioactive deposit in glaciated country[20] and the indications of gold in a series of "panned" soil samples on a mile grid, MacKay Lake area, Northwest Territories.†

* R. Sales, Paper presented at Convention of A.I.M.E., New York, March, 1948.

[17] W. O. Robinson, H. W. Lakin, and L. E. Reichen, "The Zinc Content of Plants of the Friedensville Zinc Slime Ponds in Relation to Biogeochemical Prospecting," *Economic Geology*, XLII, No. 6 (October, 1947), 572–582. See references at end of paper.

[18] H. V. Warren and C. H. Howatson, "Geogeochemical Prospecting for Copper and Zinc," *Bull. Geol. Soc. of America, 58* (Sept., 1947), 820–840.

[19] *Trans. Geological Society of South Africa*, Johannesburg (1947).

[20] F. E. Senftle, Thesis for degree of Doctor of Philosophy, University of Toronto, 1948.

† Tests by R. E. Folinsbee, University of Alberta, Dept. of Geology.

Seismic Methods.—Seismic work in mining has been almost exclusively confined to depth-of-drift or depth-to-basement determinations. Even in this work difficulty has been encountered. Working from the ice (11,000 ft/sec) first arrivals from bedrock (17,000 ft/sec) are impossible to obtain in limited confines. Sand plains require deep holes. Tests to derive the basement at Bonne Terre, Missouri, consistently picked up the crystalline limestone.

Actually the section of interest for mining prospecting is essentially the first 1,000 feet, below which depth oil interest commences. Any shooting of structure at say the 1,000-foot level would require more detail of surface configuration than is necessary for oil work, for the features sought such as silicified faults (Goldfield) or scarps (Verde Valley) might not be elevated more than 50 feet above the average level with perhaps a transverse dimension of only a few hundred feet.

Again with the possibility of detection to depth with a seismic method, it might be hoped to differentiate broad, steeply dipping formations at a given refracting horizon simply by the change in gradient of the corrected time-distance curve. Thus, if a 500-foot-broad formation of velocity 15,000 ft/sec lies between formations of velocity 17,000 ft/sec, the time-distance curve will show an offset of 0.004 seconds on crossing the 500-foot formation. Hence, such a procedure is at least theoretically possible for indicating broad formational units or even a large sulphide body beneath lake beds, and of distinguishing it from a bedrock topographic feature. However, the practical difficulties are considerable in view of the likely variability of the media and travel-time changes therein.

Also Tertiary flows may overlie or be intercalated with the rocks or lake beds of a typical area. These are likely to provide a high-velocity overlying horizon of 15,000 ft/sec. This would, of course, lead one to think of a short, multiple-refraction procedure.

Also to be considered is the question of shallow reflections from levels of 1,000 feet or less. A shallow reflection technique might permit a relatively accurate mapping of, say, bedrock features beneath drift and lake beds showing ridges and depressions, etc. This would permit geological deductions and the guiding and localizing of further exploration. But a shallow reflection technique from the surface requires explosives as energy considerations show, and with the explosives is a train of waves still being received directly when the first reflections return. Shallow reflection work has been successful in certain localities, the general technique being to use light charges, tight spreads, and oscillographs with high and low input in parallel. For mining application, any shallow reflection technique should employ portable instruments and be simple and direct.

Underground exploration from drifts and drill holes offers a fruitful field for seismic methods although here it seems that electric power supplies and a continuous- or pulsed-wave technique can be used. Frequencies will have to be kept to the audio range of 1,000 cycles per second, or less, for around a few thousand, minor fractures and slips start to disperse the energy.

H. H. Prately, of the National Geophysical Company,* made tests with conventional equipment underground in the Chief Consolidated mine, measuring the angle of ray emergence by apparent velocities with a high paper speed and attempting to plot the abnormally low- or high-velocity areas.

Grasham, of the National Research Council, Ottawa, Canada, has used crystal bunches in a diamond drill hole to give a wave envelope applying a pulsed technique to record distances. The experiments are continuing but the original frequency of around 5,000 cycles per second appears too high.

Considerable experience as to the elastic propagation of disturbances underground has been derived from the work of E. Hodgson and Z. Gibbs in their rockburst recordings at the Lake Shore mine.[21]

The hope of the seismic method underground is that by working between drifts, or between drill holes, or between mine workings and the surface, it will be possible to detect conditions beyond the range of the force-field methods. Thus in exploration work between the surface and old workings at United Verde, a million-ton sulphide lens about 250 feet in diameter and 300–400 feet away would be out of reach of any of the force-field methods and yet might cause a 0.004-second late arrival by fan shooting, assuming a 3,000 ft/sec velocity delay in the sulphides.

* Private report to Chief Consolidated Mines.

[21] E. A. Hodgson, "Seismic Research Program, Rockburst Problem, Lake Shore Mines Reports No. 1–14." Dominion Observatory, Ottawa.

WRITTEN DISCUSSION, SYMPOSIUM ON MINING GEOPHYSICS

WILLIAM H. CALLAHAN,* New York, N. Y.—Commonly oil and ore are associated with planar geologic features, the dip of which is slight for oil and steep for ore. Thus did Dr. Heiland in his introductory remarks aptly generalize the difference in geometry of occurrence of oil and ore which is critical in the design of exploration for them.

While this generalization does not imply that either oil or ore are coextensive with their respective planar features, the thought is conveyed that in plan view, an oil pool appears as an area and an ore body appears as a line. A point or spot rather than a line is the more common appearance to be expected of ore in this setting. This comes about because ore usually is not coplanar with its control but occurs as linear or podlike bodies of steep plunge in the plane. Only those linear bodies with slight plunge appear as lines. In brief, in our search for the proverbial needle, commonly we can hope for only an end view of it.

While delineation of the major planar control of ore is very essential in putting exploration on the beam, the desideratum is to focus it on a point or spot. Persistent and unsuccessful exploration on the beam only can be very wearing on philosophy as well as funds. Exploration for linear ore bodies of steep plunge is commonly conducted from points outside the major planar control of it rather than from points within it. The geometry of this drilling becomes progressively more unfavorable with depth in the topographic situations generally prevailing. Hence this type of exploration requires sharpshooting of a high order in three dimensions from a standoff position to hit the target in its most favorable presentation.

However, there are some chances for getting beam intercepts that will locate the spots of interest if the ore itself is out of range or not directly detectable by geophysical methods. Linear ore bodies are commonly the expression of a dihedral control. The planar features involved may be a favorable bed, a facies boundary, a contact, a shear or fault or fracture zone, a vein, a dike or a still, the intersection of any two or the warping of any one of which may localize ore. In cases where these features have associated physical contrasts of sufficient magnitude to permit geophysical detection, intercepts, and hence points of possible interest could be located at least in plan view. Such information would be very helpful even if the elevation of the spot were indeterminate.

All this leads to the conclusion well known to mining geophysicists, but one which I think is worth emphasizing here, that geophysical exploration for ore will generally require a vastly greater density of observing points than exploration for oil. While delineation of a major planar control of ore is a necessity and can be done if adequate physical contrast exists, by closely spaced stations on relatively widely spaced traverses, disclosure of distortions of this plane or the existence of significant intercepting features which might localize ore will require closely

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spaced traverses. And these intermediate traverses cannot safely be shortened to cover only the immediate vicinity of the major planar feature. As is the case in drilling for ore noted above, stations away from the major feature will have the best chance for successfully revealing significant information, in this case the presence and location of intercepting minor features. In brief the disclosure and resolution of points or spots of ore interest requires a screen of large area and small openings.

R. Clare Coffin,† Tulsa, Okla.—A part of the problem of applying geophysics to mining problems should include a laboratory study of physical characteristics of the rocks involved. To borrow from an experience in oil exploration, I wish to report that a continued study of the density and magnetic characteristics of cores, well cuttings, and outcrop samples has been a part of our exploration program for several years. The accuracy of the information obtained as to the properties of rocks ranged from that which is entirely satisfactory to that which is questionably of usable value. Nevertheless, we believe that our laboratory work in connection with this problem has been very profitable.

In many cases, it has made possible the prediction as to the results which would be obtained in the field over known geological structures. Subsequent field work has, in many cases, checked with surprising accuracy the predicted results. Such a procedure gives us courage in the belief that the particular formations which produce our observed effects can be isolated and identified. Within certain limits, this scheme of using laboratory data permits a rough classification of geological problems into those which may be solved by some geophysical methods and those which probably cannot be solved by these methods. It is my belief that a similar study connected with the geophysical exploration of mining problems should be a part of the required procedure.

Wm. Bradley Lewis,‡ Houston, Tex.—Experience with electrical measurements that suppress proximal effects by measuring the potential during the interval of no current flow between current reversals, has mapped sharply defined crystalline rock at depths of over 1,000 feet in a region of normal sediments. This work was presented earlier at this meeting. I believe that with some modifications this type measurement would prove very effective in solving many of the mining problems discussed in this session. These are characterized by strong electrical contrasts at depths shallow compared to those encountered in petroleum problems. Such problems should be capable of straightforward attack using gap-potential measurements.

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THEORY AND PRACTICE OF LOW-FREQUENCY ELECTROMAGNETIC EXPLORATION*

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ABSTRACT

Based directly on Maxwell's Field Equations, the extremely low end of the frequency spectrum may be reduced in first approximation to simple potential theory. The approximation theory is borne out by some field experiments, the results of which are presented. Agreement with the theory, however, requires that the ground have a very large effective dielectric constant. This conclusion is supported by previous observations by a number of independent observers. Thus, the relaxation time has been found to be extremely great, not only in observations directly on the ground, but also in small samples of mud, and the sign of an electric anomaly over a relative insulator, such as crystalline salt or gas and oil, invariably has been found to be negative. Both of these observations can be explained in terms of a very great dielectric constant. The value yielded by the present experimental work is of the order of 10^8.

THEORETICAL ELEMENTS

It is customary to base theoretical considerations, in low-frequency electromagnetic exploration, on the results derived by Sommerfeld.[1] The latter were designed for a specific purpose and have found extensive use in radio and telephony. In the exploration of the ground with extremely low frequencies, however, it is well to go back for a moment to Maxwell's fundamental theory. We shall pause for a moment, therefore, to consider the famous Field Equations. Expressed in electromagnetic units, they are:

$$\boldsymbol{i} = \frac{\partial}{\partial t}\boldsymbol{D} + 4\pi\alpha\boldsymbol{D} = \operatorname{curl}\boldsymbol{H}, \tag{1}$$

$$\operatorname{curl}\boldsymbol{E} = -\mu\frac{\partial}{\partial t}\boldsymbol{H}, \tag{2}$$

$$\operatorname{div}\mu\boldsymbol{H} \equiv 0, \tag{3}$$

$$\operatorname{div}\boldsymbol{D} = 4\pi\Gamma, \tag{4}$$

where $\boldsymbol{i}$ is the density of total electric current, $\boldsymbol{D}=\kappa\boldsymbol{E}$, is the electric displacement vector, $\alpha=\sigma/\kappa$, is the ratio of the conductivity to the dielectric constant of the medium, $\boldsymbol{H}$ is the magnetic vector, μ is the magnetic permeability, and Γ is the space density of electric charge.

Equation (3), which expresses the continuity of magnetic flux and the absence of free magnetic poles, forms the usual starting point for development of

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[1] See, for instance, Alfred Wolf, *Geophysics*, XI (October, 1946), 518.

the theory. It follows from this equation that the magnetic flux may be represented as the curl of an arbitrary vector. Since the magnetic permeability is considered constant in the present application, however, it is more convenient so to express the magnetic vector, i.e.

$$\boldsymbol{H} = \text{curl } \boldsymbol{A}, \tag{5}$$

where $\boldsymbol{A}$ is the so-called vector potential, as yet unspecified. If this expression for $\boldsymbol{H}$ be substituted into equation (2), an equation of fundamental importance in low-frequency exploration is obtained. It is

$$\text{curl}\left(\boldsymbol{E} + \mu \frac{\partial \boldsymbol{A}}{\partial t}\right) = 0, \tag{6}$$

which implies

$$\boldsymbol{E} = -\nabla\phi - \mu \frac{\partial \boldsymbol{A}}{\partial t}. \tag{7}$$

That is, the electric vector *in general* is the negative gradient of a scalar potential less the product of the magnetic permeability and the time derivative of the vector potential.

Substitution of equations (5) and (7) into equation (1) shows that the vector potential is a solution of the wave equations, i.e.

$$\mu\kappa \frac{\partial^2 \boldsymbol{A}}{\partial t^2} + 4\pi\mu\sigma \frac{\partial \boldsymbol{A}}{\partial t} = \nabla^2 \boldsymbol{A}, \tag{8}$$

provided,

$$4\pi\sigma\phi + \kappa \frac{\partial \phi}{\partial t} = -\text{ div } \boldsymbol{A}. \tag{9}$$

By taking the divergence of equation (7) and the time derivative of equation (9), it is seen that the scalar potential satisfies the equation

$$\mu\kappa \frac{\partial^2 \phi}{\partial t^2} + 4\pi\sigma\mu \frac{\partial \phi}{\partial t} = \nabla^2\phi + \text{div } \boldsymbol{E}, \tag{10}$$

which is the wave equation, provided the divergence of the electric vector vanishes. It follows from equation (1) that it does *in a homogeneous medium.* For, by taking the divergence of this equation, one obtains

$$\frac{\partial \Gamma}{\partial t} + 4\pi\alpha\Gamma = -\nabla\alpha \cdot \boldsymbol{D}, \tag{11}$$

so that, when $\nabla\alpha = 0$, or when the parameters of the medium are constant, the space density of electric charge, and hence the divergence of the electric vector,

will vanish according to an exponential factor with time. On the other hand, when the parameter, α, is not constant, so that it has a nonvanishing gradient, equation (11) shows that space charges will come into existence. In particular, if the medium has a surface of discontinuity, where the parameters change abruptly from one set of values on one side to another on the other, development of equation (11) shows that a so-called surface divergence comes into existence. That is, the divergence may be zero everywhere else but is different from zero along this surface. This means that a "surface density" of charge exists along this boundary, and this may be detected and traced by electrical measurements.

Because any irregularity in the medium, according to equation (11), gives rise to the accumulation of space charges when a current is passed through, the said irregularity will set up a perturbation potential which can be detected by electrical measurements. Equation (11), therefore, holds the key to an electric method of geophysical exploration. To work out the details of such a method with mathematical rigor would be well-nigh hopeless.

In the field of seismic exploration, which is even more complicated because the theory must be based on tensors rather than vectors, the difficulty is bypassed because it is permissible to introduce simplifying assumptions by which the theory is reduced to geometrical optics. This is not permissible in the present problem because the use of high frequencies is prohibited by so-called conductive absorption. It *is* permissible, however, to reduce the theory in first approximation to relatively simple potential theory, such as is used in full rigor for the interpretation of direct-current measurements. Equation (7) shows that when the time derivative of the vector potential is zero, as it is for direct current, the electric vector becomes simply the negative gradient of a scalar potential, this potential being the common d-c potential which has been extensively treated in the literature.[2] For extremely low frequencies, the time derivative is not quite zero. The measurements may be so arranged, however, that the vector potential has no component along the lines where measurements are carried out. The line integral of the electric vector, which is the "potential drop" measured in practice, for practical purposes then becomes derivable from a potential and is given in terms of the location of the probe electrodes.

PRACTICAL CONSIDERATIONS

Two items are of primary importance in the choice of a measuring arrangement by which the ground is to be explored electrically. They are:

1. Sufficient depth must be reached.
2. Proximate effects must be minimized.

Sufficient penetration is assured by the use of a sufficiently low frequency, assuming a large enough spread. So, it may be logically asked: Why not use zero frequency or direct current? It is true that great practical difficulties exist in the

[2] See, for instance, H. M. Evjen, *Geophysics*, III (March, 1938), 78.

measurement of truly direct current, such as the elimination of telluric currents and spurious potential drops associated with various contacts, but these conceivably could be overcome, so that sufficient accuracy could be attained. Still, direct current is not the logical answer.

By the introduction of a second independent variable, the frequency, advantages are added. In the first place, a second parameter of the ground, namely its dielectric constant, is added to the universe of discourse. It is true that it has been generally assumed that the dielectric constant may be safely neglected at the low frequencies used in geophysical exploration. Recent experiments, however, which will be presently considered, have shown that the ground materials may have a truly remarkable effective dielectric constant; it not only cannot be neglected, but it also has a definite "diagnostic" value.

In the second place, the use of a time-varying current makes possible an increase in resolving power, which has a direct bearing on the elimination of proximate effects. The theoretical foundation for this is that electrical impulses are transmitted through the ground with definitely finite speed.[3] By suppressing or eliminating early arrivals, it is thus possible to minimize and eliminate impulses which have travelled only a short distance through the ground, that is, the bulk of proximate effects. A parallel is found in seismic work where the unwanted direct wave and shallow reflections are eliminated by the use of a suppressor. In electric work this may be accomplished by the use of a commutated pulse current,[4] and measurement of the ground potential only in the gaps while no current is flowing through the energizing cables. In slightly different terms, this means that the logarithmic singularity (current-carrying cable) is completely eliminated. The current-electrode singularities also are removed with the exception of a "polarization residue," existing only in virtue of the finite dielectric constant of the ground. Late arrivals, on the other hand, signifying the depolarization of deep singularities, obtained as a result of equation (11), arrive in full force. The "gap potential" thus may be interpreted much more directly in terms of significant deep irregularities, such as the replacement of shale by limestone (reef-formation), the local presence of crystalline salt (salt domes), or the local displacement of the normally present ground waters by petroleum. Much experimental evidence exists in support of this proposition, some of which already has been presented.[5]

Although the physical background of this method of exploration, as here set forth, appears to be clear enough, a detailed theoretical treatment in usable form is still lacking.[6] The attempted rudiments of such a theory will be presented in the following, together with some supporting evidence.

[3] H. M. Evjen, *Geologie and Mijnbouw*, *1*, 1 (January, 1938), 2.

[4] H. M. Evjen, U. S. Patent No. 2,375,775, May 15, 1945.

[5] W. B. Lewis, "Electrical Surveys of Some Shallow Salt Domes," *Geophysics*, XIII (October, 1948), 595.

[6] See, however, C. W. Horton, *Geophysics*, XI (October, 1946), 595.

Approximation Theory.—With div $E=0$, an elementary solution of equation (10) may be written

$$\phi = \frac{J}{4\pi\sigma} \frac{1}{1+ju} \frac{e^{-w_1}}{r} e^{-j(w_2-\omega t)}, \tag{12}$$

where,

$$w_1^2 = w^2[(1+u^2)^{1/2} - u], \tag{13}$$

$$w_2^2 = w^2[(1+u^2)^{1/2} + u], \tag{14}$$

$$w^2 = 2\pi\sigma\mu\omega r^2, \tag{15}$$

$$u = \kappa f/2\sigma, \tag{16}$$

and where f is the frequency and ω is the angular frequency of the sinusoidal current J. By general convention $j=(-1)^{1/2}$ and only the real part of the solution, equation (12), is to be used. In the dimensionless constant, u, equation (16), it is necessary to express the conductivity in electrostatic units if the usual electrostatic units are used to express the dielectric constant.

The "numerical distance," w, given by equation (15), may be more conveniently expressed in practical units as follows:

$$w = 1.1(f/\rho)^{1/2}(r/1{,}000), \tag{17}$$

where the resistivity, ρ, is in ohm-feet, and the distance, r, in feet.

From equation (7) it is seen that the electric field may be derived from the potential (equation (12)) if the time derivative of the fector potential is zero. This is true for zero frequency, in which case the function (equation (12)) reduces to the well-known d-c potential of a point source in an infinite, homogeneous medium. The significance of this function at frequencies different from zero is now clear. It represents the scalar potential of an infinite wire around its grounded end point. To the negative gradient of this potential, according to equation (7), must be added a term depending on the time derivative of the vector potential. If the cables are properly oriented, however, the component of the vector potential along cables to probe electrodes can be made to vanish. Theoretically this can be accomplished by arranging probe cables perpendicular to current cables. This requires carrying the cables to infinity, which is not convenient in practice except in rough approximation, so it becomes necessary to compute the induction term. By rearranging the cables and repeating the measurements, it can be shown experimentally that this term must be small for low frequencies. It is then permissible to compute it by integrating the vector potential of an oscillating dipole over a convenient path, depending on the electrode arrangement used.

The solution obtained by these considerations refers to an infinite, homogeneous medium. In order to consider rigorously the effect of the always present air-ground boundary, it is necessary to use Sommerfeld's integral representation of

the vector potential. No difficulty is encountered in obtaining a formal solution. In the evaluation of the integrals involved, however, difficulty is encountered. By the usual assumption that the dielectric constant is negligible, it can be shown that some singularities of the integrand are removed. The validity of this procedure, therefore, is questionable. At any rate, the results obtained are in some respects definitely unreasonable.[7] One should expect an orderly and gradual transition from zero frequency to small but finite frequencies.

At zero frequency, the surface of the ground is a perfect reflector and is taken care of by a recognition of the fact that the current source radiates into a solid angle of 2π, instead of 4π. At small but finite frequencies, the surface of the ground remains substantially a perfect reflector. One should, therefore, expect that it still would be taken care of, in first approximation, by a factor two. This has been borne out by experiment and, therefore, will be assumed. At the surface of a homogeneous ground, the real part of the solution, equation (12) then becomes

$$\phi = \frac{J}{2\pi\sigma}\left[F_1 \cos \omega t + F_2 \sin \omega t\right], \tag{18}$$

where

$$F_1 = \frac{1}{1 + u^2}\,\frac{e^{-w_1}}{r}\,(\cos w_2 - u \sin w_2), \tag{19}$$

and

$$F_2 = \frac{1}{1 + u^2}\,\frac{e^{-w_1}}{r}\,(\sin w_2 + u \cos w_2). \tag{20}$$

No rigorous formulation of the problem, involving the gap potential, has been possible to date. The error function, which gives a convenient representation[8] for zero dielectric constant, does not apply when the latter is finite and has an appreciable value. One must therefore have recourse to a Fourier expansion. The first term in such an expansion has been found to give a fair approximation. Subject to the limitations and approximations of this development, therefore, the quadrature component of the potential given in equation (18) should represent the gap potential observed at the surface of a homogeneous earth. For a stratified earth, the perturbation potentials, arising from image sources, must be added to this solution.

EXPERIMENTAL TEST OF THEORY

To test this theory, the gap potential was measured with a Wenner arrangement of electrodes. The measurements were carried out at 26 values of frequency between 0.29 and 2.56 cycles per second at each of four Wenner spreads, having

[7] See discussion by Dr. Lewis of reference 1.

[8] C. W. Horton, *loc. cit.*

electrode separations respectively 250, 500, 750 and 1,000 feet, the center of the spread remaining the same. The results, expressed in microvolts per ampere, or microhms, are shown in Table 1. The location of the test was near the Hardy Pool, Jones County, Texas. The measurements were carried out with an apparatus previously described in the literature.[9]

TABLE 1

GAP POTENTIAL IN MICROVOLTS PER AMPERE

f	$a=$ 250	500	750	1,000 Feet
0.29	23	17	11	6
0.35	21	15	11	7
0.42	18	11	10	6
0.48	15	10	9	6
0.55	16	11	7	3
0.61	16	11	7	2
0.68	15	10	5	1
0.74	16	10	4	− 1
0.81	15	10	3	− 2
0.87	14	10	2	− 4
0.94	14	9	0	− 6
1.00	14	8	− 1	−10
1.07	14	7	− 3	−12
1.13	13	5	− 5	−15
1.20	12	4	− 8	−19
1.26	11	1	−11	−23
1.39	10	0	−14	−29
1.52	9	− 2	−19	−37
1.65	8	− 6	−24	−45
1.78	6	− 9	−29	−54
1.91	4	−11	−34	−62
2.04	3	−13	−38	−69
2.17	1	−18	−45	−76
2.30	0	−22	−51	−85
2.43	−2	−26	−56	−93
2.56	−3	−31	−62	−102

For an electrode separation, $r=a$, equation (12) yields the following:

$$Q_1 = \frac{1}{\pi\sigma}\left[F_2(a) - F_2(2a)\right]. \tag{21}$$

This is the primary effect, or the effect which would be present if the ground were homogeneous. For a stratified ground, image sources and sinks come into play, the effect of which may be represented as

$$Q_i = \frac{1}{\pi\sigma}\left[F_2(\sqrt{a^2 + h_i^2}) - F_2(\sqrt{4a^2 + h_i^2})\right]. \tag{22}$$

There is, however, also a phase shift by the reflection when the dielectric constant has an appreciable value, so that this expression is not complete.

[9] W. B. Lewis, *Geophysics*, X (January, 1945), 63.

No precautions were taken to eliminate the induction term or the time derivative of the vector potential in the present experimental setup. By considering the vector potential of an oscillating dipole, one arrives at the following estimate of this term:

$$Q_m = - Mw^2 e^{-w_1} \cos w_2 \tag{23}$$

where the "mutual inductivity," M, has the numerical order of magnitude of one.

An inspection of the parameters entering into the primary effect reveals that the latter may well be expanded into a power series in terms of the numerical distance. Noting that

$$u = kf = sw^2, \tag{24}$$

where

$$s = \frac{k\rho}{1.21}(1{,}000/a)^2, \tag{25}$$

the power series to fifth-order terms may be written

$$Q_1 = w^2 U_1/\pi\sigma\alpha, \tag{26}$$

where

$$U_1 = 1 - M + s/2 - (1 - M)w + \tfrac{1}{2}[(1 - M)s + 1 - 2M/3]w^3 - \cdots . \tag{27}$$

Referring to the definition of w in equation (15), it is seen that this may be considered as a power series in terms of the square root of the frequency. To be specific, equation (26) may be written

$$Q_1 = \frac{1.21}{\pi} f(a/1{,}000)(A_1 + A_2 f^{1/2} + A_3 f + \cdots)10^{-3}. \tag{28}$$

The coefficients in this expansion depend on the electrode separation, a. In particular, the coefficient A_1 has a term varying as a^{-2} in virtue of $s/2$. This is the term referred to above as the "residual polarization," giving rise to a simple pole singularity for $a=0$. By equations (16) and (24)

$$k = 1.72\kappa\rho 10^{-11}, \tag{29}$$

where ρ now is expressed in ohm-feet and κ is expressed in the usual electrostatic units. It will be noticed that this term is characteristic of the primary effect and is absent from possible reflections. If an analysis of the data in Table 1 should reveal a simple pole-electrode singularity, this can therefore be ascribed to the primary effect.

Least-square analysis of the data, retaining only the first three terms in the expansion, equation (28), yields the following values for the coefficient A_1:

TABLE 2

COEFFICIENT A_1 FOR DIFFERENT ELECTRODE SEPARATIONS

a	A_1	$0.125\,(1{,}000/a)^2-0.07$
250	1.95	2.070
500	.57	.570
750	.33	.292
1,000	.20	.195

The computed A_1, less a constant 0.07, has been plotted on logarithmic paper in Figure 1. A straight line with slope -2 will be seen to fit the data well. These observations, therefore, indicate the following analytic representation:

$$A_1 = 0.125(1{,}000/a)^2 + 0.07 = s/2 + (1 - M). \tag{30}$$

Consequently, by equations (25) and (29)

$$\kappa\rho^2 = 189 \times 10^8. \tag{31}$$

Since the square of the ground resistivity, expressed in ohm-feet, is of the order of 200, the value of the dielectric constant, indicated by these observations, is of the order of 10^8. The inductivity, M, is of the order of unity, as correctly predicted by the approximation theory.

DISCUSSION

The data of Table 1 indicate strong reflections, which is to be expected at the location where this experiment was performed. It is fortunate that the reflections contribute nothing to the singularity at $a=0$, so that the conclusions drawn from Table 2 and Figure 1, particularly equation (31), are valid regardless of the interfering reflections. This conclusion is so startling that it can be accepted only with some hesitation and calls for a repetition of the experiment at a favorable location and under carefully controlled conditions.

The electrode singularity observed conceivably might be caused by leakage current during the gap when no current is supposed to flow through the current electrodes. Or it might be due to polarization of the probe electrodes, if any portion of the potential circuit were closed during the "current on" period. Blocking switches in both current and potential circuits, however, rule out this possibility.

The question naturally is asked: Does any other and independent evidence exist, bearing out such an unheard-of value of the dielectric constant? The answer is that a considerable amount of evidence exists but not all has been published, and that which has been published to some extent has been ignored. For instance, the fine structure observed in transient measurements, and used in geophysical interpretation, has been dismissed by many as a physical impossibility, probably caused by experimental error. Likewise, the fine structure found

in dispersion graphs,[10] which has been used extensively in structural interpretation with good results. This fine structure is indeed a physical impossibility on the basis of a theory which ignores the dielectric constant. With a dielectric constant such as that derived from the present experiment, however, it is readily

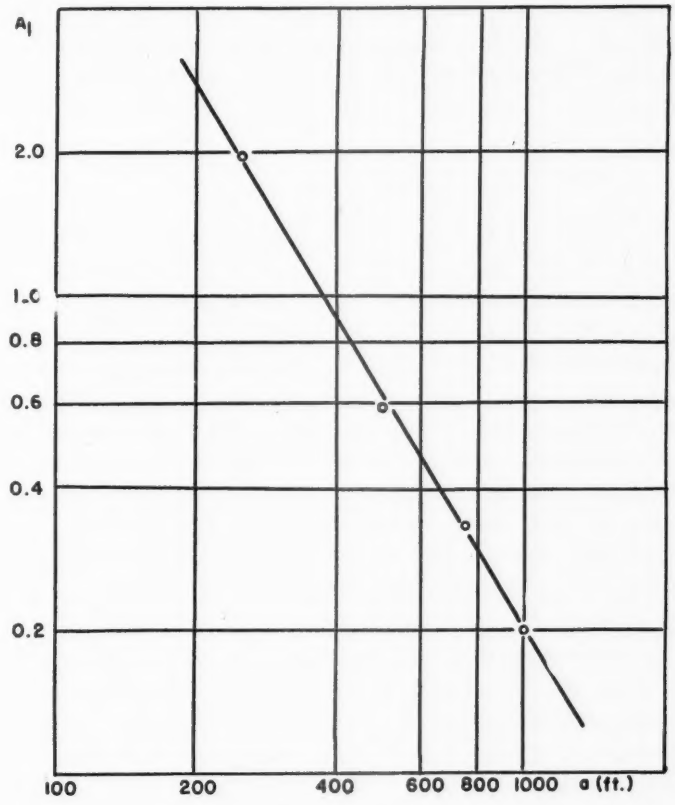

FIG. 1. Coefficient A_1 as function of a.

seen that resonance phenomena might easily account for the reproducible and correlatable fine structure.

Another phenomenon, which bears directly on the dielectric constant, is the remarkable value of relaxation time observed in the course of direct-current measurements.[11] This conceivably might be explained in terms of the stratified nature of the ground, in conjunction with equation (11) of this paper. That is, with space charges accumulated in virtue of the surface divergence at numerous

[10] H. M. Evjen, Austin Meeting, A.I.M.E., October, 1942.

[11] See, for instance, Thomas S. West and Clarence C. Beacham, *Geophysics*, XI (October, 1946), 491–504.

interfaces, the ground might easily assume characteristics similar to those of an electrolytic condenser. This, however, does not explain the relaxation time observed on soil samples containing shaly or clayey material. In carefully controlled experiments conducted by Dr. W. B. Lewis and reported verbally to the writer, values of the relaxation time were observed which could be explained only in terms of values of the dielectric constant, such as those derived from the present experiment. Another piece of evidence is the sign of the electric anomaly observed over a relative insulator, such as rock salt. If a current per cm.^{2} i_n is passed from a medium (1), into a medium (2), a surface density of charge is formed, which is given by

$$\gamma = (i_n/4\pi)[\rho_2\kappa_2 - \rho_1\kappa_1]. \tag{32}$$

It will be noticed that the sign and magnitude of this surface density depends on the dielectric constant. That is, it is the product of resistivity and dielectric constant which determines the sign and magnitude of the anomalous surface charge which can be detected by measurements. It will be seen that if the contrast ratio in the dielectric constant is in the neighborhood of unity, as has been generally assumed, the sign and magnitude of the anomalous charge is determined by the resistivity contrast. The sign associated with a relative insulator, such as rock salt, then would be positive. Instead, it invariably has been found to be negative, which is explained in terms of a very large dielectric constant, reduced to normal values at the depth of the relative insulator. Such a large possible contrast in the dielectric constant naturally has a considerable value in the art of geophysical exploration with time-varying electric currents. With truly direct current it plays no part, because the observational phenomena here are governed by Laplace's equation, in which the dielectric constant does not enter.

Finally it may well be asked what effect such a large dielectric constant has on the attenution of electromagnetic waves in the ground. The answer is given by equation (13), which shows that the "attenuation distance," w_1 is reduced for increasing values of u. A rough estimate of the effect shows that transmission of quite high frequencies can be expected over distances as great as 500 feet, depending, of course, on the conductivity of the ground. The effect, therefore, is not sufficient to be of practical importance.

ELECTRICAL SURVEYS OF SOME SHALLOW SALT DOMES*

W. BRADLEY LEWIS†

ABSTRACT

Consideration of the perturbation potentials associated with geological features indicates the superiority of gap-measurements over in-phase measurements. Measurements of the gap-potential over two Gulf Coast salt domes show sharp anomalies readily correlated with known geology.

GENERAL DISCUSSION

The neglect of electrical methods during the past decade can be attributed to an understandable prejudice. This prejudice has arisen through the failure of conventional-type measurements to obtain significant results from sufficient depths to be of importance to the petroleum geologist. Progress has been hindered considerably by the complexity of ideas and terminology associated with the conventional apparent-resistivity measurements. It is in order here to examine what is measured, what is implied in the measurements, and, if necessary, to criticize the use of terms that may handicap interpretation.

In the conventional measurements, and in the measurements to be discussed, a potential difference is observed. This is attributable to a current impressed on the earth. Insofar as the ground is linear,‡ the observed potential difference is proportional to the energizing current. For this reason the significant quantity is the ratio of the observed potential difference to the energizing current. This quantity has the dimensions of an impedance. It may be conveniently expressed in millivolts per ampere, or microvolts per ampere, depending on the magnitude of the potential observed.

If direct current is used, the potential per unit current can be multiplied by a suitable geometric factor which will convert this quantity to a resistivity expressed in ohm-feet, ohm-meters, or ohm-centimeters, depending on individual preference. This resistivity is a purely fictitious quantity and is called the "apparent resistivity." It is the resistivity that a homogeneous earth must have to give the observed potential per unit current for the chosen electrode pattern.

If the apparent resistivity varies as the electrode pattern is changed, the earth is not homogeneous. In line with certain assumptions, a layered earth with beds of definite resistivities and thicknesses can be constructed to fit a set of data which shows apparent resistivity as a function of electrode pattern. The chief purpose in varying the pattern is to eliminate the effect of the surface layer.

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‡ Many experiments have been performed by the author to test the linearity of the ground. In all cases, the ground was found to be linear within the limits of accuracy of the measurements.

A more direct approach results from by-passing the concept of resistivity and looking directly at the potential field.

The potential is due to the singularities at the energizing electrodes produced when current passes through them into the earth, and to singularities existing at interfaces where there is a change in the electrical parameters of the earth, in particular, a change in resistivity. These interfacial singularities can conveniently be represented by images. Thus the observed potential difference can be separated into that associated with the electrode singularities, and that associated with the image singularities. The first effect may be termed the direct potential and the second, the perturbation potential.

Usually the perturbations are small compared to the direct effect. However, the perturbations contain the interesting information. Conventional methods attempt to eliminate the direct effect by making several measurements, involving varying fractions of direct and perturbation effects. Then, by calculation, the direct effect can be eliminated. Although this device has proved effective to depths of a few hundred feet, it has not been satisfactory to several thousand feet.

Another device for eliminating the direct effect is used in the Elflex method, viz.: to make the electrode singularities zero during the time the potential difference is being measured. This is accomplished by using a commutated current with a relatively short energizing interval compared to the gap interval between reversals. The potential measuring circuit is connected to the probe electrodes during the gap.

Several papers[1,2,3,4] have appeared during the past few years dealing with low-frequency electrical measurements on the earth. The advantage of quadrature measurements was pointed out by Horton.[5] Much greater suppression of the direct effect attends gap measurements. This point has not been sufficiently emphasized, nor is it generally appreciated.

The foregoing general discussion has been presented as background against which to view the results of measurements over two salt domes. Use has been made of simple direct-current concepts which apply only loosely to the problem. However, they are useful in giving the order of magnitude of expected effects.[6] It will be seen that the total measured potential per unit current is in microvolts per ampere. For direct current, or in-phase measurements at the frequencies used, the measurements would be in millivolts per ampere. This in itself shows that the direct effect is greatly suppressed.

[1] H. M. Evjen, "Utility of Electrical Methods," *Geophysics*, VIII (1943), 146–156.

[2] W. B. Lewis, "Working Depths of Low Frequency Electrical Prospecting," *Geophysics*, X (1945), 63–75.

[3] C. W. Horton, "On the Use of Electromagnetic Waves in Geophysical Prospecting," *Geophysics*, XI (1946), 505–517.

[4] Alfred Wolf, "Electric Field of an Oscillating Dipole," *Geophysics*, XI (1946), 518–537.

[5] C. W. Horton, *loc. cit.*

[6] W. B. Lewis, *loc. cit.*

The significance of the results is more readily understood if the causes associated with the anomalies are conceived as being due to images from a reflecting interface, rather than in terms of apparent resistivity, a meaningless term for gap-potential measurements.

An observed anomaly can be associated with a perturbation absent in normal parts of the survey. Its presence indicates either a strong change in the reflecting power of an interface, which can be associated with a strong change in the resistivity of one of the beds bordering the interface, or the introduction of a new interface with strong electrical contrast to the normal sediments.

Changes in the reflecting power of an interface can be associated with change in content of a porous formation, say from salt water to oil. The piercement-type salt dome offers a good example of an interface existing only in a restricted part of an area. Both cases represent an effect associated with local changes in content rather than with structural changes.

NATURE OF MEASUREMENTS

The measurements in these surveys were of the Elflex type whereby the potential per unit current is measured during the gap interval between current reversals. The commutation is such that the current flows during 0.4 of a half cycle, then after 0.1 half cycle, the potential is measured during 0.4 half cycle. After another 0.1 half cycle the events repeat except with sign reversed. A null reading is obtained by opposing the potential produced between the probe electrodes with a measuring potential proportional to the energizing current. This is obtained by a suitable coupling network linking the current circuit to the probe circuit.

RESULTS

The first survey, Figure 1, was made over the Long Point dome in Fort Bend County, Texas. This has salt at a little more than 1,000 feet. The outline of the dome is well established by drilling. Sulphur is produced in the northeastern portion of the dome.

The electrode pattern was of the Wenner type, 3,000 feet between current electrodes and 500 feet between probe electrodes. The contours are made on the directly read quantity at 4.0 cps. It is of interest that as sharp an anomaly was shown when the current spread was reduced to 1,500 feet. A few direct-current readings were taken on and off the anomaly. These and the computed apparent resistivity showed no anomaly.

The second survey, Figure 2, was made over the San Felipe dome in Waller and Austin Counties, Texas. Here a 3,000-foot, 1,000-foot Wenner spread was used. The contours are made on the readings observed at 0.5 cps. The depth to the salt is about 3,500 feet. The geology is considerably more complicated than in the Long Point dome, and the electrical picture is not as clear cut. The presence of petroleum in the Frio at a depth of 2,600 feet tends to confuse the electrical picture.

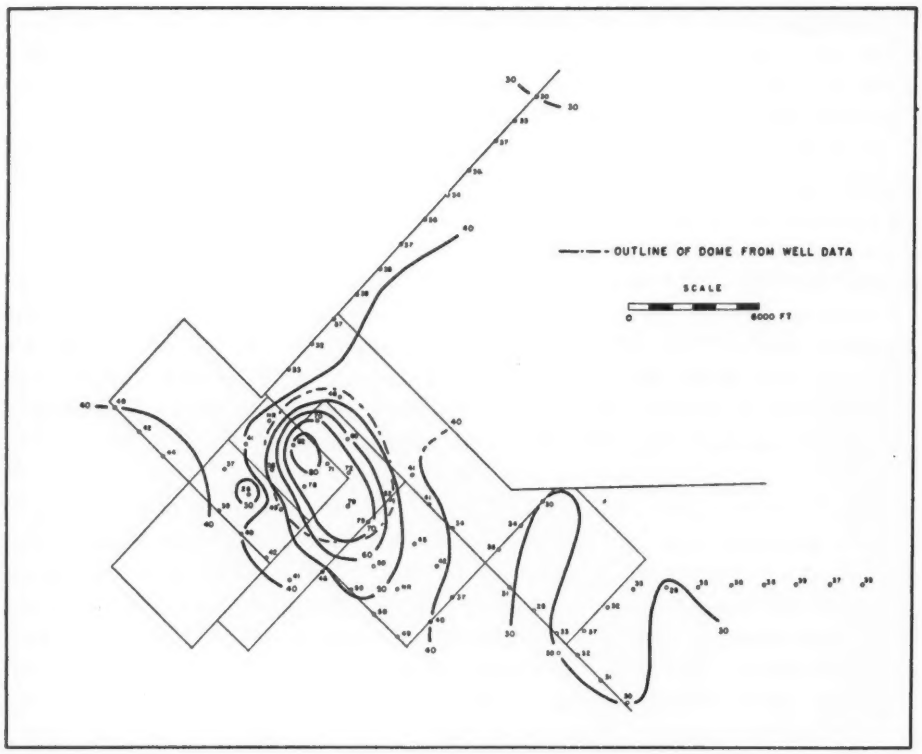

FIG. 1. Electrical survey of Long Point Salt dome. Contour interval 33.3 microvolts per ampere.

DISCUSSION OF RESULTS

The observed slide-wire readings may be converted to microvolts per ampere by multiplying by a constant. This constant is 3.3 for a reading at 4.0 cps. and 0.38 for a reading at 0.5 cps. The dependency of this constant on frequency is determined by the characteristics of the coupling network that furnishes the measuring potential. Thus the contour interval is 33 microvolts per ampere on the Long Point map, and 7.5 microvolts per ampere on the San Felipe map.

The Long Point anomaly is about 100 microvolts per ampere above the average background which is seen to vary gently between 100 and 120 microvolts per ampere. The San Felipe anomaly varies from about 10 to 30 microvolts per ampere above its immediate background, depending on what part of the dome is observed. The order of magnitude of the anomalies is correct for effects from these depths.

SUMMARY

Electrical surveys conducted over two salt domes show well-defined anomalies that correlate with known geology. Of the two pictures the one with the fewer geological and electrical complications, namely Long Point, gave a remarkably clear-cut picture. The constancy of background is noteworthy. The Long Point

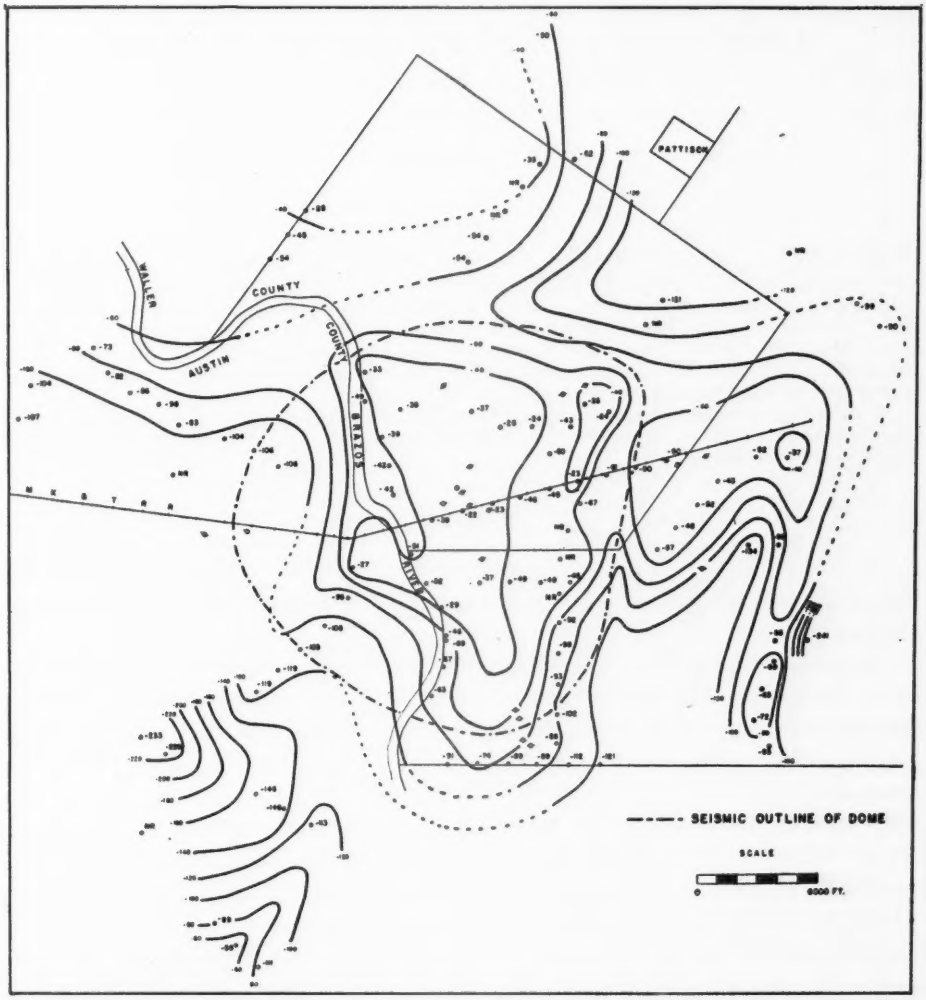

FIG. 2. Electrical survey of San Felipe Salt dome. Contour interval 7.5 microvolts per ampere.

dome is sharply defined by drilling. The San Felipe dome is known by drilling and seismic work.

These domes were chosen to demonstrate the practical application of electrical measurements because they are free from man-made electrical disturbances that are associated with producing fields, and because in both cases the subsurface conditions are well known.

ACKNOWLEDGMENTS

The author wishes to thank the Superior Oil Company for permission to publish these results and the Kirby Petroleum Company for furnishing the seismic picture of the San Felipe dome.

A NEW METHOD OF INTERPRETATION OF SELF-POTENTIAL FIELD DATA*

L. DE WITTE†

ABSTRACT

In this paper a new, efficient method is worked out for the interpretation of self-potential field data. Interpretation of location, depth and dip of the ore body is made, using a pattern of equipotential lines. The negative center and the positive maximum of the potential are found and also the so-called "mid-value" point. The dip α, can be determined accurately for values between 5° and 85°. The method cannot be used for vertical polarization. The depth and location can be found with relative accuracy for $\alpha > 10°$. The main advantage of this new method is the ease of interpretation and a greater accuracy for the high-dip angles.

It should be stressed that, for correct and accurate interpretation, the positive maximum is as important as the negative center. Therefore, it should be carefully sought during the field work, and mapped to its full extent.

INTRODUCTION

The existing methods of interpretation of self-potential data, obtained from prospecting for ore bodies, are cumbersome and commonly involve a large amount of guesswork.

An elaborate theory for the surface distribution of potentials was worked out by A. Petrovski.[1] The method of interpretation given by Petrovski uses the current densities, which are proportional to the derivatives of the potential curves for a fixed direction of traverse. This obviates taking into account a base-line potential.

A later method given by W. Stern[2] is based on formulas derived from assuming the ore body to be a polarized bar. The potentials measured in the field are used as such, which gives inaccuracies due to the absence of a fixed base line, relative to which the potentials are defined. In the theory the potential at a large distance is assumed to be zero. In the field, however, the zero-potential is difficult to obtain due to the presence of spurious potentials caused by vegetation and percolation. It is also difficult to predetermine how far one has to go to find the "infinity-potential" for practical purposes, as the positive maximum caused by the ore can be far from the center of the ore body for low-dip angles.

The interpretation here presented is based on Petrovski's theory, assuming the ore body to be a polarized sphere. A "mid-value" point is introduced which eliminates the zero-line difficulties and does not require the use of current densities, saving much work and minimizing errors in the interpretation.

* California Institute of Technology, Division of Geological Sciences, Contribution No. 469. Manuscript received by the Editor June 17, 1948.

† California Institute of Technology, Pasadena, California.

[1] A Petrovski, *Philosophical Magazine*, 5 (1928), 334, 914, 927.

[2] W. Stern, *Trans. A.I.M.E. 164* (1945), 189.

The "mid-value" point is an improvement on the "half-value" point idea which was outlined by C. A. Heiland,[3] for a vertically polarized sphere.

As only three points are used for the interpretation, all of which are well defined by the equipotential pattern, inaccuracies due to distortion by topography are kept to a minimum.

THE THEORY OF INTERPRETATION

Figure 1 represents a hidden polarized sphere in a semi-infinite isotropic medium, and its image at equal distance above the flat boundary surface.

The vertical plane through the plus and minus pole is called the plane of

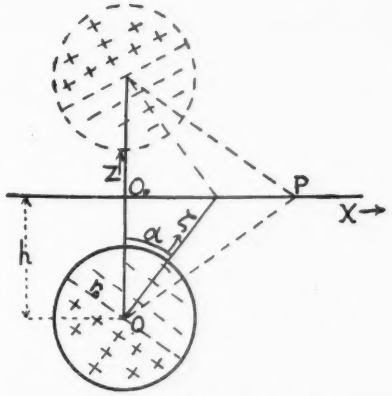

FIG. 1. Polarized body and its image.

polarization (here the plane of the paper). The x-axis is the intersection line between the plane of polarization and the horizontal boundary surface. The z-axis is vertically upward. The origin O_0 is vertically above the center of the hidden sphere. The polarization of the sphere is assumed to diminish by the cosine law with respect to the angle which is formed by the given direction and the axis of polarization (ζ).

$$e = E \cos \theta.$$

For any point p on the x-axis, Petrovski calculated the potential due to the field of the hidden sphere to be:

$$V = \frac{ER_0^2}{2} \frac{h \cos \alpha + x \sin \alpha}{(x^2 + h^2)^{3/2}}. \tag{1}$$

To find the abscissae of the maximum and minimum points, we take the derivative:

[3] C. A. Heiland, *Geophysical Exploration* (New York: Prentice-Hall, Inc., 1940), 673.

$$\frac{dV}{dx} = \frac{ER_0^2}{2}\left\{\frac{-3hx\cos\alpha + (h^2 - 2x^2)\sin\alpha}{(x^2+h^2)^{5/2}}\right\},$$

$$3hx_m\cos\alpha = (h^2 - 2x_m^2)\sin\alpha,$$

$$x_m = -3/4h\cot\alpha \pm \sqrt{h^2/2 + 9/16\cot^2(\alpha)\cdot h^2},$$

$$a = 1/2(x_{m_1} - x_{m_2}) = h\sqrt{1/2 + 9/16\cot^2\alpha}. \tag{2}$$

The length $2a$ is the distance between the maximum and minimum point of the potential along the x-axis.

$$\frac{x_m}{h} = -3/4\cot\alpha \pm \sqrt{1/2 + 9/16\cot^2\alpha}. \tag{3}$$

Figure 2 gives the potential profile for $\alpha = 45°$ and shows the relative position

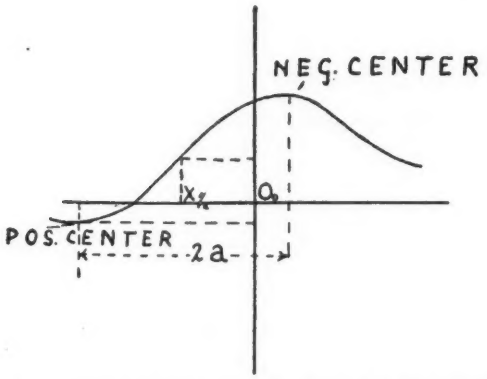

FIG. 2. Profile of the self-potential curve along the x-axis.

of the negative center and positive maximum. The potential is taken negative upward, while x is positive in the direction of the negative center.

We now define the "mid-value" point as the point where the potential $V_{1/2}$ has a value equal to $\frac{1}{2}(V_{\text{maximum}} + V_{\text{minimum}})$ and located between the negative and positive centers. We call its abscissa: $X_{1/2}$.

From equation (1) with $ER_0^2/2 = A$, we have:

$$\frac{V_m h^2}{A} = \frac{\cos\alpha + x_m/h\sin\alpha}{[(x_m/h)^2 + 1]^{3/2}}, \tag{4}$$

$$V_{1/2} = 1/2(V_{\max} + V_{\min}) = F(\alpha)\frac{A}{h^2}. \tag{5}$$

For any given value of α, we can calculate the above defined $(F\alpha)$ by first calculating $X_{\max}/h$ and $X_{\min}/h$ from equation (3). Substitution into equation (4) gives V_{maximum} and V_{minimum}.

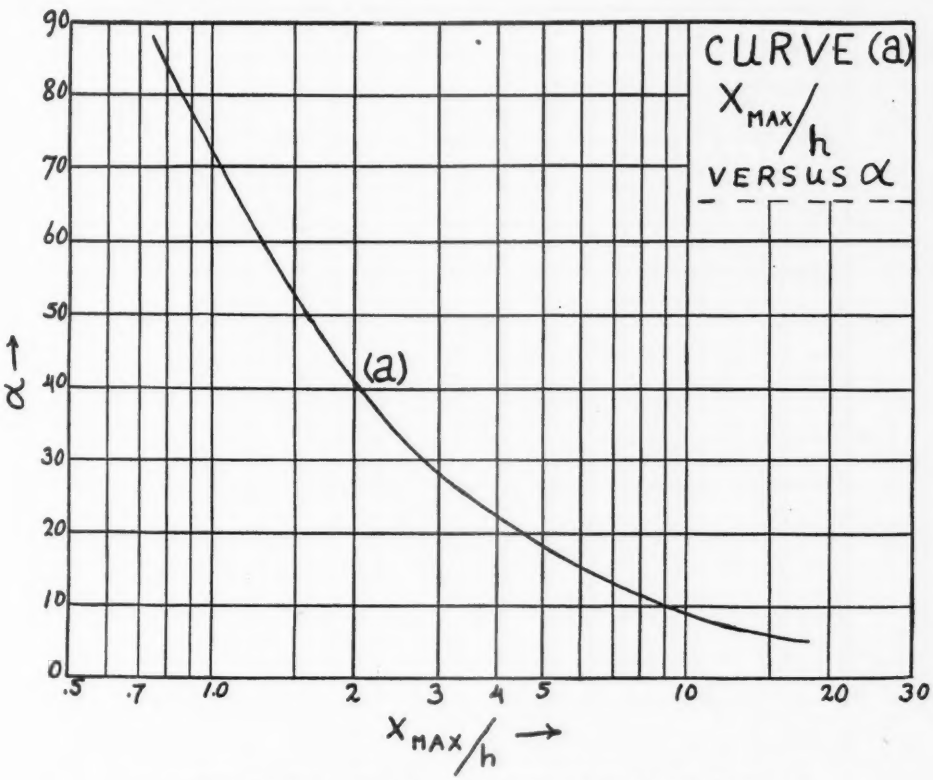

FIG. 3. The ratio of x_{max} divided by the depth as a function of the angle α.

Figure 3, curve (*a*) shows x_{max}/h as a function of α. Figure 4, curve (*b*) gives x_{min}/h and Figure 5 curve (*c*) gives a/h, obtained from equation (2).

For $X_{1/2}$ we obtain from equations (1) and (5) the identity

$$F(\alpha)\frac{A}{h^2} = \frac{A}{h^2}\,\frac{\cos\alpha + x_{1/2}/h \sin\alpha}{[(x_{1/2}/h)^2 + 1]^{3/2}}.$$

This gives $x_{1/2}/h$ as a function of α. See Table 1.

TABLE 1

α	a/h	$x_{1/2}/h$	$a/(x_{min}-x_{1/2})$	$a/(x_{max}-x_{1/2})$
5	8.60	−0.721	11.47	0.523
10	4.31	−0.573	5.90	0.546
20	2.18	−0.579	3.126	0.595
30	1.48	−0.493	2.20	0.647
40	1.14	−0.407	1.75	0.701
50	0.947	−0.323	1.48	0.755
60	0.829	−0.240	1.30	0.811
70	0.757	−0.160	1.19	0.870
80	0.719	−0.079	1.08	0.932

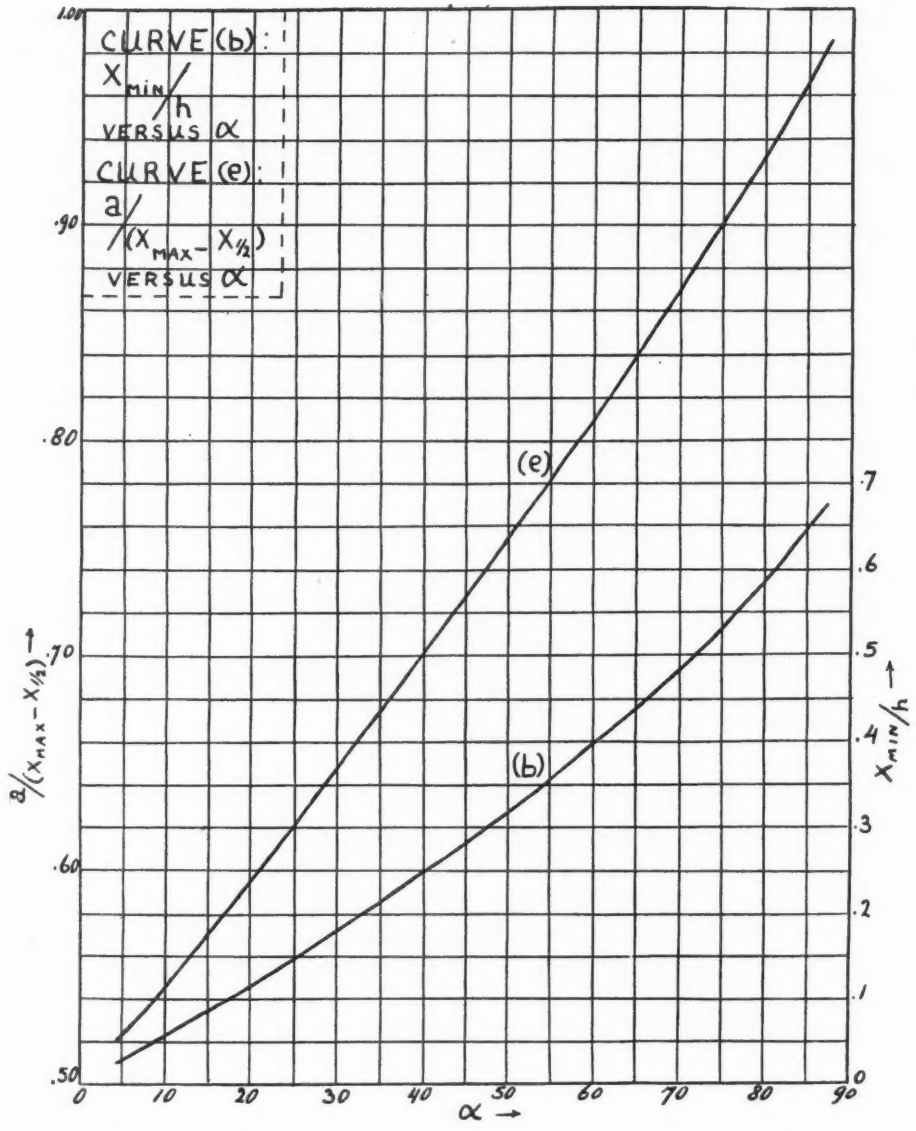

FIG. 4. Curve (b): x_{min}/h as a function of α. Curve (e): $a/(x_{max}-x_{1/2})$ as a function of α.

Table 1 also gives a/h for the entire range of α (from $a/(x_{min}-x_{1/2})$ and $a/(x_{max}-x_{1/2})$.

The latter values were obtained by first finding $(x_{min}-x_{1/2})/h$ and $(x_{max}-x_{1/2})/h$ and then dividing these quantities by a/h.

The length $(x_{min}-x_{1/2})$ and $(x_{max}-x_{1/2})$ can be measured along the x-axis. Curves (d) and (e) show them as functions of α.

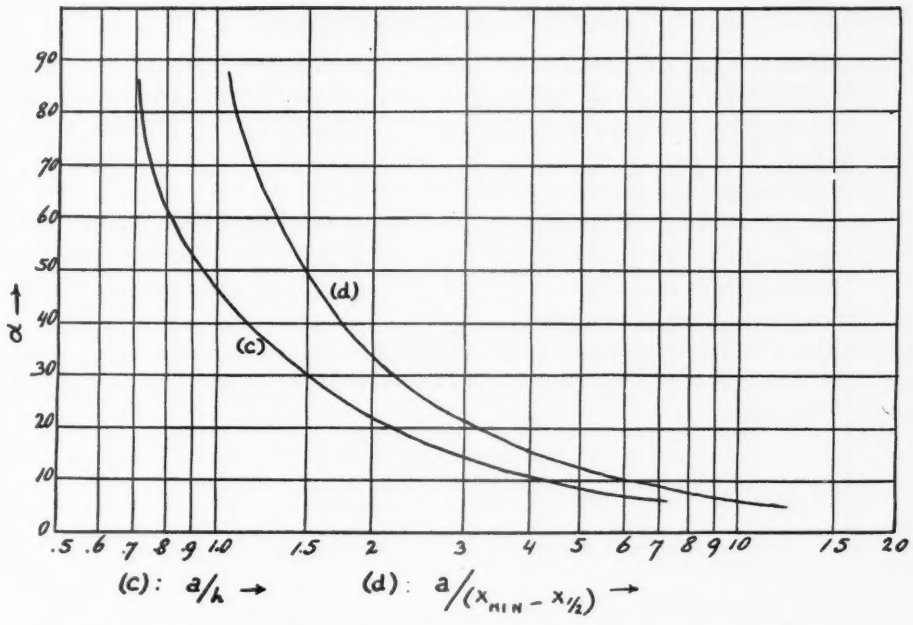

FIG. 5. Curve (c): a/h as a function of α. Curve (d): $a/x_{\min}-x_{1/2}$) as a function of α.

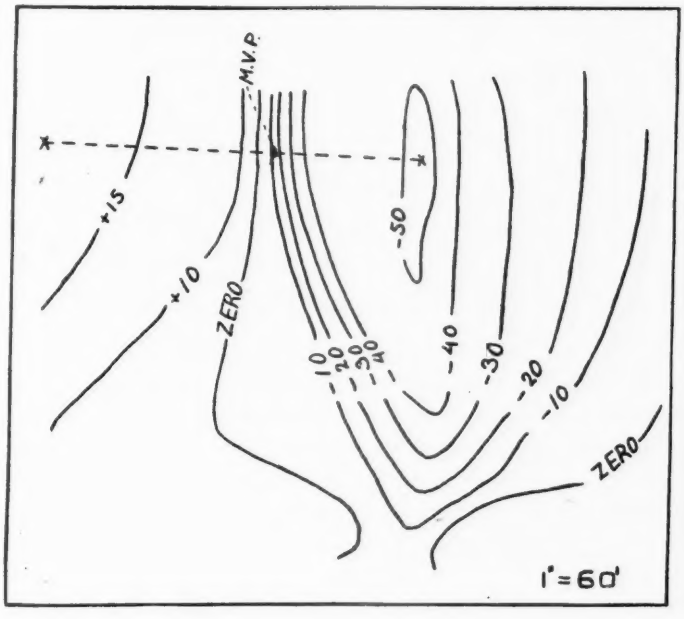

FIG. 6. Big Bend self-potential anomaly.

PROCEDURE OF INTERPRETATION

1. Measure a as half the distance between the negative and positive center.
2. Measure $x_{min} - x_{1/2}$ and (or) $x_{max} - x_{1/2}$ respectively as the distance between the negative and positive center and the mid-value point. Divide a by the latter.
3. From curve d or e find α.
4. For the value of α obtained find a/h from curve c. This gives us h.
5. From curve a or b find x_{max} or x_{min} which gives the distance of O_0 (the vertical projection of the center of the ore body on the surface) from the positive or negative center.

In practice h denotes the depth to the point where the water table intersects the ore body. The "center" is the midpoint of the section of the ore body made by the plane of the water-table.

NUMERICAL EXAMPLES

a) Big Bend anomaly (Surcease mine), see Figure 6.

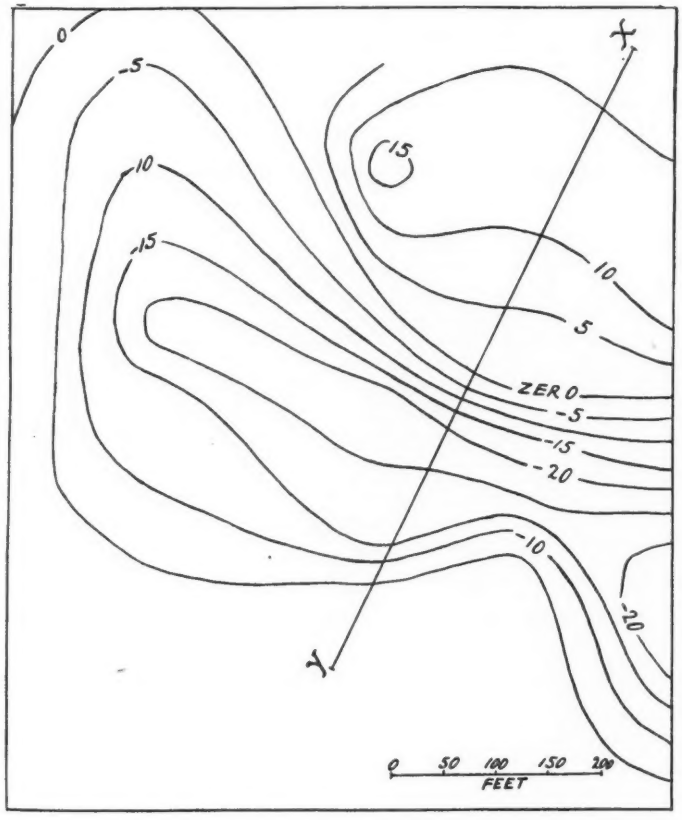

FIG. 7. Self-potential anomaly at Hope, British Columbia.

This example was taken from the professional thesis of S. Yüngül,[4] who interpreted the curves by Petrovski's current-density method.

The positive maximum value is approximately 18 mv. Midpoint value: $\frac{1}{2}(18-50)=-16$; $a/x_{\min}-x_{1/2}=1.3$.

Curve (*d*) gives $\alpha=60°$. For $\alpha=60°$, curve (*c*) gives $a/h=0.84$, $2a=180$ feet, so $h=90/0.84=107$ feet. From curve (*b*): $x_{\min}/h=0.395$, $x_{\min}=42.8$ feet, Yüngül found $\alpha=60°$ $h=106$ feet.

b) Hope mine (British Columbia), see Figures 7 and 8.

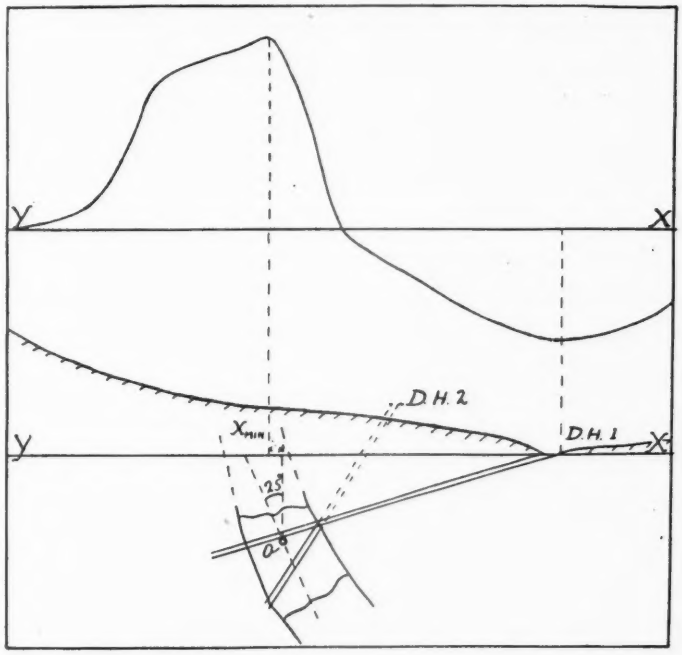

FIG. 8. Cross section and self-potential profile of the Hope anomaly along the line *XY* of Figure 7.

The equipotential pattern was constructed from a series of potential profiles given by J. J. Breusse.[5] The cross section (Fig. 8) was taken from an article by E. Poldini.[6] The potentials in Figures 7 and 8 are expressed in arbitrary units.

The anomaly is no type-example for representation by a polarized sphere. However, along the lines of greatest current density, the potential distribution appears to deviate very little from that for a polarized sphere.

[4] S. Yüngül, *Prof. Thesis*, California Institute of Technology (1945).
[5] J. J. Breusse, *Engineering and Mining Journal*, *133* (1932), 338.
[6] E. Poldini, *The Mining Magazine*, *60* (1939), 25.

Measurements along the line xy give the following results:

$V_{min} = -22$ units; $V_{max} = 12$; $V_{1/2} = -5$;

$a/(x_{min} - x_{1/2}) = 2.52$.

Curve (d) gives $\alpha = 25°$. From curve (c) for $\alpha = 25°$: $a/h = 1.75$; $h = 79$ feet.

Curve (b): $x_{min}/h = 0.15$ or $x_{min} = 12$ feet.

The thus determined center of the ore body and also the calculated dip are indicated in Figure 8. The agreement with the data obtained from the drill holes 1 and 2 is perfect.

Acknowledgments are made to Dr. G. Potapenko under whose direction the work has been carried out and to Mr. William E. Messner of the Surcease Mining Company for permission to publish the above data.

BIOGEOCHEMICAL INVESTIGATIONS IN BRITISH COLUMBIA*

HARRY V. WARREN† AND ROBERT E. DELAVAULT†

ABSTRACT

Biogeochemistry, like geophysics, is a useful tool for those who seek ore in areas where outcrops are few, vegetation heavy, or glacial drift widespread.

Knowledge of the normal amounts of, as well as the ratios existing between, any elements in the selected organs of appropriate trees and lesser plants growing under the various geological and geographical conditions involved in a chosen area, makes it possible to discover biogeochemical anomalies should any be present.

Experience in British Columbia suggests that in a search for copper or zinc, a study of the ratios existing between the amounts of these elements present in young twigs affords a simple and usually effective way of detecting anomalies. By using twigs, it is practical to carry on investigations during seasons when weather conditions make some types of prospecting impossible.

Biogeochemistry is not a rival of geophysics, geology, or hard work as a means of finding ore. It is another tool which, if employed intelligently under appropriate but not necessarily ideal conditions and in conjunction with other suitable tools, can do much to assist in a search for hidden ore.

INTRODUCTION AND EARLY HISTORY

Recently Rankama,[1] Lundberg,[2] and Warren and Howatson[3] reviewed some of the latest work which has been done in biogeochemistry. Rankama referred particularly to those ore bodies which cannot be directly located by known geophysical methods and mentioned especially the advances that have been made in chemical, biogeochemical, and geobotanical prospecting. Anybody interested in obtaining a general background of the relative position of biogeochemistry in the present prospecting picture may refer to any of the above articles.

The senior author has for a long time felt that there was a gap to be filled between the work of the man picturesquely if not altogether correctly referred to as "the old-time prospector" and that of the professional engineer. In spite of a greater knowledge of geology, mineralogy, and other useful subjects than his forebears had, the prospector of today still relies to a considerable extent, at least in British Columbia, on his pick, shovel, and pan. During hours spent in the company of these useful but uninspiring tools, the senior author conceived the idea of letting trees take over some of the task of underground exploration. Once conceived, the idea grew rapidly, nourished and abetted by the proddings of mosquitoes and other forms of wild life. Then, at the critical moment, Mr. and Mrs. Dor-

* Presented at the Annual Meeting of the Society, April 28, 1948, Denver, Colorado. Manuscript received by the Editor June 16, 1948.

† University of British Columbia, Vancouver.

[1] Kalervo Rankama, "Some Recent Trends in Prospecting," *Mining and Metallurgy*, June, 1947.

[2] Hans Lundberg, "On the History of Geophysical Exploration," *The Can. Min. and Met. Bull.*, *41* (March, 1948), 171–185.

[3] H. V. Warren and C. H. Howatson, "Biogeochemical Prospecting for Copper and Zinc," *Geol. Soc. Am. Bull.* (1947), 803–920.

bils offered the Department of Geology and Geography of the University of British Columbia a prize for the best essay on "Botany and Geology." This offer unwittingly played the role of midwife, for with its help a new research project was born, to be known as "Botany and Subsurface Geology." After a precarious early life, and in spite of a most austere diet, the infant grew so that in name at least it reached the state of childhood. Botany and subsurface geology has become biogeochemical prospecting and seems destined to grow in stature in the next decade.

Although aware that some work of the sort contemplated had been done elsewhere, the senior author, in the winter of 1944–45, still did not know what had been done in Scandinavia during the last decade.

Coincident with the commencement of field work in British Columbia, an attempt was made to discover what had been done elsewhere in the field of biogeochemistry. In spite of the incompleteness of our reviewing, two facts appeared to stand out: a wealth of information and experience was available to those who wished to commence biogeochemical investigations, but it was also apparent that the great bulk of the work in this field had been carried out either in connection with agriculture or by scientists who apparently had had the benefit of first-class laboratory facilities.

In view of these two facts, we decided that the most useful course for us to follow was that of attempting to explore the possibility of developing field methods which would enable a trained man, not necessarily of research calibre, to detect biogeochemical anomalies in the field.

A modest research project was then drawn up, and this, together with an equally modest budget, was presented to those from whom financial support was expected. The authors anticipated a measure of healthy scepticism, but they were almost dismayed at their inability to obtain any financial support, even from those organizations from whom it had confidently been expected. However, even though financial support was not forthcoming, a gratifying measure of cooperation was offered, and as has already been mentioned, Dean Buchanan and Professor Williams almost alone managed to obtain a few hundred dollars which enabled our project to go forward.

The results of our first year's work far exceeded our expectations and in May, 1946, the senior author presented these results in a paper which was read to the Geological Section of the Royal Society of Canada. This paper was later published in revised form in the *Bulletin of The Geological Society of America*.[4] Later, financial support came from The Geological Society of America and this support has enabled us to carry on further investigations. Some of the results obtained for these investigations follow and some will also appear in a later *Bulletin of The Geological Society of America*.

SELECTION OF METHODS IN BRITISH COLUMBIA

Obviously any scheme to find hidden ore bodies in British Columbia must take into account the geological and geographical conditions which exist in the prov-

[4] *Ibid.*

ince. British Columbia today has within its borders only one great operating mine, the Sullivan, probably the largest producer of lead and zinc combined in the world. She has, however, a large number of prospects and smaller operating mines which are geographically well dispersed and geologically of many types. Deposits of gold, silver, lead, zinc, copper, nickel, manganese, chromium, cobalt, tungsten, molybdenum, mercury, and antimony, to name a few, are to be found in various parts of the province. A wide range of climate, from marine west coast to continental, and a great diversity of rocks, in both age and type, guarantee a stimulating background for research. They also ensure many complications.

British Columbia has been heavily glaciated and many tens of thousands of square miles lie covered with a mantle of glacial drift. In many areas, this drift lies over rocks known to be geologically favorable for the finding of ore. On the coast, heavy rainfall results in dense vegetation which hides the bedrock over large areas. To these complications must be added many mountain ranges which, with their rugged topography and attendant transporation problems, do much to test the ingenuity of the would-be mine finder. In British Columbia virtually every mining camp, but not every ore body by any means, has resulted from the discovery of veins which outcropped. Considering all the factors involved, the wonder is not that we have so few mines in British Columbia, but that we have had the good fortune to find as many as we have.

Bearing the above facts in mind, the reader will appreciate that for our first experiments, we did not consider either botanical or chemical methods. Both of these may be tried at a later date. However, the sparseness of residual soil over our ore bodies, and the wide variations in climate, indicate that our chances of finding trees or lesser plants which can be correlated with a particular ore below the surface, as might be done in portions of the United States, Australia, or Africa, are poor. Furthermore, from the point of view of a prospector, it must be remembered that many of the plants which might be considered indicative of a specific mineral can only be recognized readily by their flower, which appears for only a relatively short period.

The objections to taking water samples are entirely different, but they, too, are of a practical nature. In the first place, throughout the dryer parts of the province, there are seldom streams situated where one would want to take samples. In the second place, there is the practical difficulty of taking many samples from their source to a place where they can be tested. Metal or fiber cases invite salting, and glass containers do not lend themselves readily to transportation. In the third place, most of the creek water in those areas where there is running water never penetrated the ground, and indeed in places consists largely of melted snow. Soil sampling also poses its own problems, of which the difficulty of obtaining a true sample and of preventing accidental salting of a sample are perhaps the most obvious.

Lake and bog ores and limonites offer real possibilities of providing clues in the search for ores, and we propose in British Columbia to follow up these possibilities at an early date.

Having thus eliminated for the time being the more obvious chemical and geobotanical methods, we concentrated our early efforts in the field of biogeochemistry. In the tables which follow, the copper and zinc ratios are mostly calculated directly from the amounts of metals present in the sample. These ratios, therefore, do not always check with the numbers given in parts per million which may be, for small amounts of copper, quite rough approximations. For example, either 2.6 or 3.4 ppm of copper would be recorded as 3 ppm. Thus, in the copper-to-zinc ratio, the second figure often has little significance.

BIOGEOCHEMICAL PROBLEMS

THE SELECTION OF SUITABLE PLANT ORGANS

Other workers had established that, as far as zinc and copper were concerned, trees and lesser plants carried these elements in order of decreasing abundance in their leaves or needles, fruit, bark, and wood.

Wood.—In spite of its low content of zinc and copper, wood was investigated. We felt that wood might have two great advantages which could outweigh its disadvantages. By taking samples with an auger, it would be possible not only to sample large trees whose roots might be expected to penetrate to greater depths than those of smaller trees, but also to obtain samples of heart wood free from all possibility of having been salted by dust particles.

TABLE 1

ANALYSES OBTAINED FROM WOOD

	Specimen No.	Cu	Zn	Cu/Zn	Specimen No.	Cu	Zn	Cu/Zn
Pseudotsuga taxifolia (Douglas Fir)	91(−)	3	28	0.11	106(+Zn)	2	7	0.29
	20(−)	3	1	3.0	136(+Zn)	1	6	0.17
	44(−)	2	8	0.25	3(+Cu)	5	3	1.7
					30(+Cu)	1	8	0.13
Larix occidentalis (Western Larch)	85(−)	1	8	0.13	100(+Zn)	2	7	0.29
					130(+Zn)	1	3	0.30
Pinus contorta (Lodgepole Pine)	29(−)	1	5	0.20	43(+Cu)	3	1	3.0
	86(−)	1	19	0.05	140(+Zn)	1	10	0.10
Alnus sinuata (Green Alder)	94(−)	2	8	0.25	109(+Zn)	2	19	0.10
					139(+Zn)	1	2	0.50
Salix sp. (Willow)	93(−)	2	28	0.07	108(+Zn)	3	26	0.11
					133(+Zn)	2	18	0.11
Acer glabrum (Rocky Mountain Maple)	96(−)	1	5	0.20	111(+Zn)	1	13	0.08
					139(+Zn)	1	5	0.20
Thuya plicata (Western Red Cedar)	23(−)	1	12	0.08	9(+Cu)	7	3	2.33
Tsuga heterophylla (Western Hemlock)	26(−)	1	1	1.0	16(+Cu)	4	9	0.44

Unfortunately, not only did the wood contain relatively small amounts of copper and zinc, but the amounts that were present proved to be unrealiable as a guide to the presence or absence of nearby ore.

Throughout the remainder of this paper, copper and zinc will be reported in parts per million (ppm) of air-dried plant material. The terms *positive* and *negative* will be used to indicate the known presence or absence of nearby copper and zinc mineralization of any importance. Amounts of less than 1 ppm are reported as 1, and all figures given are to the nearest whole number.

Table 1 serves to illustrate the results we obtained with the wood from several species of trees. It must be admitted that more precise analytical work would have indicated more useful results. However, none of our samples was run on less than 10 grams and some on as much as 100 grams. For practical purposes we decided to eliminate wood.

Bark.—We next turned our attention to bark. Table 2 summarizes some of our results. Some of the variations in Table 2 are believed to be the result of our

TABLE 2

ANALYSES OF BARK

	Specimen No.	Cu	Zn	Cu/Zn	Specimen No.	Cu	Zn	Cu/Zn
Pseudotsuga taxifolia (Douglas Fir)	19(−)	2	27	0.07	6(+Cu)	5	1	5.00
	50(−)	6	5	1.20	36(+Cu)	1	10	0.10
	82(−)	6	61	0.10	97(+Zn)	4	65	0.17
					134a(+Zn)	5	57	0.08
					134(+Zn)	5	22	0.20
Larix occidentalis (Western Larch)	84(−)	1	42	0.02	99(+Zn)	3	36	0.09
	166(−)	2	18	0.11	129(+Zn)	1	10	0.10
					148(+Zn)	5	35	0.14
Pinus contorta (Lodgepole Pine)	49(−)	4	1	4.00	35(+Cu)	1	15	0.01
	87(−)	3	65	0.05	141(+Zn)	2	90	0.03
	174(−)	14	28	0.50	153(+Zn)	4	38	0.11
Salix sp. (Willow)	120(−)	6	192	0.03	114(+Zn)	2	120	0.02
	179(−)	10	3	3.30	161(+Zn)	1	20	0.05
Acer glabrum (Rocky Mountain Maple)	122(−)	7	72	0.10	105(+Zn)	6	120	0.05
					138(+Zn)	6	76	0.08
Populus tremuloides (Aspen)	183(−)	5	1	5.00	145(+Zn)	3	13	0.23
Tsuga Mertensiana (Mountain Hemlock)	213(−)	3	1	3.00	206(+Cu)	31	3	10.0
Tsuga heterophylla (Western Hemlock)	25(−)	8	4	2.00	15(+Cu)	5	13	0.46
Thuya plicata (Western Red Cedar)	8(−)	1	1	1.00	22(+Cu)	6	12	0.50

selecting dead bark in some instances and in others, bark containing a considerable amount of sap. Some of the low assays are open to question. Nevertheless, in spite of these possible explanations of the unencouraging results, we felt it wise to concentrate on other organs, particularly because work on these other organs, conducted with similar care, immediately yield infinitely more promising results.

TABLE 3

ANALYSES OF CONES

	Specimen No.	Cu	Zn	Cu/Zn	Specimen No.	Cu	Zn	Cu/Zn
Pseudotsuga taxifolia (Douglas Fir)	172(−)	5	82	0.06	98(+Zn)	3	22	0.15
	200(−)	3	15	0.20	135(+Zn)	5	26	0.18
	P2c(−)	4	18	0.22				
	P8(−)	4	15	0.27				
	18(−)	7	11	0.70				
	83(−)	3	15	0.23				
Larix occidentalis (Western Larch)	89(−)	3	18	0.17	104(+Zn)	3	12	0.25
	199(−)	1	22	0.05	131(+Zn)	10	68	0.15
	169(−)	6	380	0.01	151(+Zn)	8	320	0.02
Pinus ponderosa (Ponderosa Pine)	171(−)	3	55	0.05				
Pinus contorta (Lodgepole Pine)	175(−)	1	142	0.01	191(+Zn)	1	24	0.03
	204(−)	1	6	0.20	152(+Zn)	8	300	0.03
	77(−)	3	9	0.33				
	81(−)	5	11	0.45				
Picea Engelmani (Engelman's Spruce)	66(−)	3	33	0.09				
	79(−)	4	33	0.11				
	79(−)	7	53	0.14 (Seeds and scales only)				

Cones.—Some of our earliest results on cones were most encouraging but were not confirmed by later work. Table 3 summarizes our findings. The figures in Table 3 proved to be very disappointing until we looked further into the problem. Naturally we suspected salting and that may have accounted for some of the discrepancies. Another explanation may be discounted: several cones were broken up into their component parts and a spectroscopic examination of these parts revealed that the seeds were richer than the remainder of the cone. It was originally thought that as in some cones the seeds had fallen out, whereas in others they remained, thereby accounting in part for the disappointing results. A consideration of the relative weight of the seeds and the cones ruled this out, the seeds for most species representing a negligible percentage of the weights of the cones. However, this problem was not further investigated. Field work clearly demonstrated the futility of attempting to use cones. In addition to a tendency to lose their seeds on some occasions and not on others, and to be liable to salting, the fruit was more often than not conspicuous by its absence on just those trees which were in a significant place for sampling.

This led us to consider leaves and needles. With leaves and needles we obtained our first satisfactory results. These results have shown, to the author's satisfaction at least, that biogeochemistry can be applied on a practical scale in the field.

Leaves or Needles.—Table 4 indicates a pretty fair cross section of the type of

TABLE 4

ANALYSES OF LEAVES AND NEEDLES

	Specimen No.	Cu	Zn	Cu/Zn	Specimen No.	Cu	Zn	Cu/Zn
Pseudotsuga taxifolia	K9V*(−)	6	33	0.17	73(+Cu)	14	7	2.0
Douglas Fir	K9 (−)	3	23	0.15	73V(+Cu)	2	5	0.40
	5 (−)	2	31	0.05				
	5S† (−)	3	37	0.10				
	H.I. (−)	3	28	0.10				
Tsuga heterophylla	77(−)	1	15	0.06	71(+Cu)	14	9	1.55
(Western Hemlock)	H4(−)	3	10	0.24	218(+Cu)	20	1	20.0
Alnus sinuata	230(−)	13	21	0.62	223(+Cu)	700	70	10.0
(Green Alder)								
Shepherdia canadensis	167(−)	5	28	0.18	163(+Zn)	12	50	0.24
(Soopolallie)								
Echinopas horridus	228(−)	26	1‡	26.0	225(+Cu)	1050	71	14.79
(Devil's Club)								
Vaccinium spp.	227(−)	21	17	1.24	217(+Cu)	60	15	4.0
(Blueberry)								
Populus tremuloides	182(−)	20	113	0.18	147(+Zn)	12	206	0.06
Pteridium aquilinum	28(−)	11	1§	11.0	11(+Cu)	75	8	9.38
(Bracken)								
Pachystima myrsinites	54(−)	2	8	.25	40(+Cu)	13	52	0.25
(False Box)	123(−)	2	20	0.10	101(+Zn)	8	96	0.08
					144(+Zn)	8	50	0.16
Salix sp.					118‖(+Zn)	20	305	0.07
(Willow)					112(+Zn)	23	264	0.09
					127(+Zn)	15	127	0.07
					165(+Zn)	10	114	0.08

* V=relatively young needles or leaves.
† S=relatively old needles or leaves.
‡ This analysis was made for copper and is probably unduly low for zinc.
§ This analysis was made for copper and is probably unduly low for zinc.
‖ This sample was originally collected as a negative sample. It is now thought to be positive.

results obtained. These results have not been selected in such a way as to paint too rosy a picture: they represent analysis selected at random. Individually the results in Table 4 may not appear conclusive, but collectively they are quite satisfactory.

Leaves or Needles and Twigs (boughs).—In order to eliminate as many of the factors as possible which cause variations in the copper and zinc content of trees, a number of samples of evergreens were taken over negative and positive areas of restricted size. The samples were taken from the tops of small trees and from the tips of branches of other smallish trees whose tops were too high to reach. Into some samples the collector threw a few cones for good measure, a fact

TABLE 5

ANALYSES OF ZINC CONTENT IN LEAVES OR NEEDLES AND TWIGS

	Sample No.	Cu	Zn	Area	Cu	Zn	Cu/Zn
Pinus contorta	39	+	−	Copper Mountain	13	53	0.25
(Lodgepole Pine)	53	?	−	Copper Mountain	6	18	0.37
	H.3		−	Hope	5	52	0.10
Average of 7 samples (1)	Cu−	Zn+		Sullivan	4	280	0.01
Average of 10 samples (2)	Cu−	Zn+		Sullivan	5	126	0.04
Average of 5 samples (3)	Cu−	Zn+		Sullivan	3	55	0.06

TABLE 6

ANALYSES OF COPPER CONTENT IN LEAVES OR NEEDLES AND TWIGS

Sample No.			Area	Cu	Zn	Cu/Zn
Tsuga heterophylla	77	Cu− Zn−	Britannia	2	15	0.13
(Western Hemlock)	71	Cu+ Zn−	Britannia	38	21	1.81
	H.4	Cu− Zn−	Hope	4	14	0.29
(Average of 10 samples)*	−150 ft.	Cu+ Zn+	Britannia	186	233	0.80
(Average of 17 samples)*	+150 ft.	Cu+ Zn+	Britannia	34	47	0.72

* Taken below copper precipitation plant.

not learned until these particular samples were milled. Fortunately, as Tables 5 and 6 indicate, no great harm seems to have been done. In Table 5 the groups of samples were taken in increasing distance from the ore. The overburden varied in thickness from 10 feet to over 50 feet. The No. (3) group was all taken more than 300 feet from any known ore, and there was known to be between 50 and 60 feet of overburden in this section.

The question of "physical" salting may reasonably arise. Fortunately, of the seventeen samples, two were taken from across a little creek which more or less effectively cut off chemical contacts but not any mechanical contacts with the other fifteen samples. These two samples were low in copper, 4 and 5 ppm respectively, and showed Cu/Zn ratios of 0.07 and 0.08, the only two samples in the group to fall below a figure of 0.30.

We have no satisfactory negative samples of *Picea sitchensis* (Sitka spruce) in the Britannia area, because of the difficulty of getting definite negative samples. However, the average of 26 samples, taken over an area in which under-

ground work had shown that ore lay below 10 to 20 feet of drift, ran Cu 12 and Zn 30, giving a Cu/Zn ratio of 0.40. Incidentally, this ore body, unlike most of the ore bodies at Britannia, carried no zinc.

In a general way, it seems reasonable as a starting point to assume that if, where there are more than 30 inches of rain and the soil is at least slightly acid, the young portions of the boughs of coniferous trees carry more than 10 ppm of copper and/or have a copper to zinc ratio of better than 0.2, there may be copper concentrations in the vicinity. Our studies in limestone areas are incomplete, but results so far obtained suggest that the absolute amount of copper may have to be only 5 ppm to become suggestive, but the significant Cu/Zn ratio does not appear to be correspondingly decreased.

Where the soil is slightly acid and coniferous boughs run consistently well over 50 ppm of zinc and have a Cu/Zn ratio of less than 0.10, there may be zinc concentrations about; where the zinc consistently runs over 100 ppm the chances of finding zinc ore are even better.

Where deciduous trees are being considered, it appears that their capacity to take up zinc is much greater than that of their coniferous brethren. Deciduous trees may carry more than 100 ppm of zinc in their leaves and yet not indicate the presence of any significant concentrations of zinc. However, we have not obtained any results as high as those reported by Robinson, Lakin and Reichen[5] or by Vogt, Braadlie, and Bergh.[6] Whether this is the result of our climate, the presence of antagonistic elements, or mistakes on our part, we do not know.

However, where deciduous leaves or twigs and leaves tend consistently to run better than 100 ppm of zinc or 20 ppm of copper, the possibility of ore being in the vicinity must be considered.

Twigs.—Unfortunately, although the use of twigs with either needles or leaves seemed most promising at the time the work was undertaken, several faults have since become evident.

This type of sample tended to be bulky and the joints between needle or leaf and bough offered a resting place for salting particles of dust and dirt. Then, too, when the bough dried, needles and leaves tended to break off, and even after milling and careful sampling, we found it difficult to get identical and satisfactory samples for ashing and analysis.

None of the above objections was more than annoying and in a laboratory could be overcome without too much difficulty. It was another, and at first sight relatively minor matter, which led us to investigate yet another method of taking samples. When leaves or needles are ashed, they tend to produce a fluffy ash;

[5] W. O. Robinson, H. W. Lakin, and Laura E. Reichen, "The Zinc Content of Plants of the Friedensville Zinc Slime Ponds in Relation to Biogeochemical Prospecting," *Econ. Geol.* XLII (1947), 572–582.

[6] Thorolf Vogt, O. Braadlie, and H. Bergh, "Bestemmelse Cu, Zn, Pb, Mn, og Fe i planter fra Rørosfeltet" ("Determination of Copper, Zinc, Lead, Manganese, and Iron in Plants from the Røros Area"), *D. K. Norske Videnskabers Selskab, Forhandlinger, 16,* 15 (1943), 55–58.

TABLE 7

ANALYSES OF TWIGS

Number of Sample	Rock Over Which Sample Taken	(∓)	Cu	Zn	Cu/Zn
Pseudotsuga taxifolia (Douglas Fir)					
K.1	Conglomerate	−	4	60	0.07
K.7	Sandstone	−	6	34	0.19
K.9	Sandstone	−	4	46	0.08
K.2 (a)	Shale and glacial drift	−	4	69	0.05
K.2 (b)	Shale and glacial drift	−	5	43	0.12
K.8	Shale (but roots close to sea water)	−	6	41	0.15
G.D.1	Glacial drift (hard pan)	−	5	31	0.16
4	Quartz feldspar porphyrite	−	5	32	0.19
5	Gabbro diorite porphyrite	−	6	43	0.12
6	Grandiorite porphyrite	−	5	44	0.14
H.1	Grandiorite porphyrite	−	5	40	0.13
J.T.1.N.	Andesite	−	5	40	0.13
J.T.1.S.	Andesite	−	2	19	0.11
J.T.3	Andesite	−	5	28	0.18
V.1201	Limestone (but close to sea water)	−	4	27	0.15
V.1205	Limestone (but close to sea water)	−	3	26	0.12
V.1206	Limestone (but close to sea water)	−	1	20	0.05
B.73	Schist (twig 2 years old)	+Cu	23	12	1.92
B.73	Schist (twig 3 years old?)	+Cu	13	12	1.08
V.8	Limestone (on old mine dump)	+Cu	5	25	0.20
V.2	Limestone (on old mine dump)	+Cu	3	24	0.12
V.3	Limestone (on old mine dump)	+Cu	3	28	0.11
Tsuga heterophylla (Western Hemlock)					
77	Schist and glacial drift	−	9	43	0.21
K2(a)	Shale and glacial drift	−	10	133	0.08
K2(b)	Shale and glacial drift	−	7	44	0.17
J.T.1	Andesite	−	2	40	0.05
V.22	Limestone	−	3	43	0.07
V.22	Limestone	−	3	37	0.08
71	Schist and glacial drift	+Cu	130	65	2.00
Abies amabilis (Fir)					
K8(a)	Shale (but roots close to sea water)	−	6	30	0.20
K8(b)	Shale (but roots close to sea water)	−	6	45	0.13
4	Quartz feldspar porphyrite	−	5	21	0.24
6	Grandiorite	−	5	44	0.11
J.T.3	Andesite	−	5	24	0.21
74	Schist and glacial drift	+Cu	30	24	1.25
Salix sp. (Willow)					
K2(a)	Shale and glacial drift	−	1	27	0.05
K.8	Shale (roots close to sea water)	−	22	87	0.25
K.7	Sandstone	−	9	106	0.08
K.9	Sandstone	−	4	35	0.11
4	Quartz feldspar porphyrite	−	5	47	0.11
6	Granodiorite	−	9	110	0.08
H.6	Grandiorite	−	10	78	0.13
J.T.1.N.	Andesite	−	7	64	0.11
J.T.1.S.	Andesite	−	8	47	0.17
J.T.3	Andesite	−	13	28	0.46
Alnus rubra (Red Alder)					
K.2.(a)	Shale and glacial drift	−	7	19	0.36
K.2.(b)	Shale and glacial drift	−	2	15	0.13
K.8	Shale (but roots close to sea water)	−	10	26	0.40
K.7	Sandstone	−	7	39	0.17
K.9	Sandstone	−	3	13	0.25
G.D.	Glacial drift	−	6	20	0.30
4	Quartz feldspar porphyrite	−	5	16	0.31
6	Granodiorite	−	5	20	0.25
H.5	Granodiorite	−	7	37	0.18
J.T.1.N.	Andesite	−	9	29	0.31
J.T.1.S.	Andesite	−	9	33	0.27
J.T.3.	Andesite	−	11	25	0.44

and, furthermore, if milled, there seems to be a possibility of the ashing being incomplete even after several hours. It will be understood that ashing must be carried on at as low a temperature as is practical. Incomplete ashing may cause trouble later on during the analytical work.

Young twigs ash more readily and do not produce a fluffy ash. In short, they contain more copper and zinc per cubic inch of crucible, and it takes less energy to prepare the ash for analysis, an important point to remember in the field. In addition the samples are easy to take, to return to camp, to ship if that be necessary, and to clean of superficial dust by washing. Furthermore, deciduous trees can be sampled when their leaves are off, and as deciduous trees tend to be much more lively indicators of mineral concentrations, this is a great advantage.

We have compared the zinc and copper content of young twigs and of the attached leaves and needles. In some instances twigs are richer, but in other samples the reverse holds. The copper/zinc ratios vary a little, and may do so quite markedly in limestone areas where copper seems to be much lower proportionately than zinc.

For the past few months we have used twigs for most of our sampling, only taking boughs for comparisons. So far our experience has been that although the young twigs do not show the spectacularly high copper and zinc results occasionally given with leaves or cones, they are just as reliable. Wood older than two years seems to be lower in copper or zinc, and whatever may be the explanation, we have tried to standardize our sampling, taking one-year-old twigs where this is practical.

The last three samples of Douglas fir in Table 7 indicate the trouble encountered when one tries to look for copper in a limestone area. Unfortunately we have as yet no samples of Douglas fir twigs taken over a positive zinc area.

Unfortunately, we have yet to collect samples of twigs from satisfactory positive areas. We have done enough work to know that there are no great differences between the copper and zinc content of fresh young twigs and young green leaves or needles. It is possible that seasonal variations are responsible, in part at least, for the fact that twigs are occasionally richer and occasionally poorer in copper and zinc than the leaves or needles they bear. Keeping these remarks in mind, a few of the determinations in Table 7 made on willow may be of interest.

In taking the samples of willow in Table 7 for control purposes we assumed that all were negative. Two, K.8 and J.T.3, were abnormal and of these two, the former had roots which probably had access to salt sea water and the latter was some 500 feet away from a small copper showing unknown to us at the time when we were making our collections. Compare these results with those of leaves taken near the Sullivan, where, of five positive sets of collections, no one averaged less than 225 ppm of zinc and one set of five samples actually averaged 732 ppm of zinc. It must be stated, however, that these exceptionally high results were obtained from trees growing within 100 feet of mineralization and through only from 10 to 20 feet of overburden.

We had no positive twigs of red alder, but we did by chance have a copper positive sample of *Alnus sitchensis*. It ran: Cu: 69, Zn: 93, Cu/Zn: 0.74. Two samples of leaves of *Alnus rubra* from a copper and zinc positive area at Britannia on schist and glacial drift averaged: Cu: 170, Zn: 310, Cu/Zn: 0.55.

Referring to the red alder samples in Table 7, it will be noted that the only two samples to carry over 10 ppm or a Cu/Zn of 0.40 or greater, are the K.8 and J.T.3 samples, the precise samples which showed similar discrepancies in the consideration of willow in Table 7. It seems almost certain that it will be variations of this type which will eventually be used in biogeochemical prospecting.

Many more figures could be cited, but they would only serve to illustrate the unexpected difficulties we encountered in the early stages of our work. It is almost certain that many of our early zinc analyses were low—this will be referred to later under analytical methods. To sum up, we believe that, taking all factors into consideration, young twigs provide the most satisfactory samples from trees or lesser plants.

THE SELECTION OF SUITABLE SPECIES OF TREES AND LESSER PLANTS WITH WHICH TO ESTABLISH "NORMALS" IN AN AREA

This problem often solves itself. In the field we have found that nature frequently settles it in a positive fashion. In the few areas in which we have worked, there have usually been only one or two species abundant and widespread enough to be at all suitable for biogeochemical prospecting. It is all very well to know that young twigs are desirable, but just how to obtain them from our forest giants whose lowest branches are fifty feet above ground is a problem.

In many areas sagebrush, lupin, or even sunflower, may have to be used. It may well be that we shall find collector plants which will collect copper and zinc in the same manner in which some species of Astragalus collect selenium.

Our own experience has suggested that willow—we may have to learn to distinguish between the various species which grow in British Columbia—is an excellent tree to use where practicable. It carries fair amounts of copper, its roots seek out underground watercourses, it is easy to identify even in winter, and it usually provides an abundance of young twigs.

Again neglecting different species, alder would seem to be a useful tree. Apparently it carries, or perhaps we should say tends to carry, less copper and zinc than willow, and its copper/zinc ratio may be a little higher. It too, like willow, is easy to recognize in winter and seems to be able to exist on less water.

Of the gymnosperms there is little of value that we can say at the present time. *Pinus contorta* (lodgepole pine), *Pseudotsuga taxifolia* (Douglas fir), *Tsuga heterophylla* (western hemlock), and *Picea sitchensis* (Sitka spruce) have all proved useful, largely because they happened to be abundant in the areas of economic mineralization where we were carrying on investigations.

Table 8 shows how each species tends to carry varying amounts, both absolute and relative, of copper and zinc. With the exception of the willow and alder sam-

TABLE 8

QUANTITIES OF ZINC AND COPPER IN VARIOUS SPECIES OF TWIGS

Rock type	Species	*Pseudotsuga taxifolia* Douglas Fir			*Thuya plicata* Western Red Cedar			*Tsuga heterophylla* Western Hemlock			*Salix sp.* Willow			*Alnus rubra* Red Alder			*Gaultheria shallon.* Salal		
Conglomerate K.1	Cu Zn Cu/Zn	4	60	0.07	4	9	0.44	no sample available			no sample available			no sample available			3	13	0.19
Sandstone K.7	Cu Zn Cu/Zn	6	34	0.19	2	10	0.17	no sample available			9	106	0.08	7	39	0.17	not collected		
Sandstone K 9	Cu Zn Cu/Zn	4	46	0.08	2	12	0.17	no sample available			4	35	0.11	3	13	0.25	3	18	0.19
Shale & glacial drift K.2.a	Cu Zn Cu/Zn	4	69	0.05	2	15	0.11	10	133	0.08	1	27	0.05	7	19	0.36	not collected		
Shale & sea water K.8	Cu Zn Cu/Zn	6	41	0.15	3	19	0.16	no sample available			22	87	0.25	10	26	0.40	not collected		
Glacial drift	Cu Zn Cu/Zn	5	31	0.16	3	11	0.27	no sample available			no sample available			6	20	0.30	not collected		
Quartz feldspar porphyrite 4	Cu Zn Cu/Zn	5	32	0.19	no sample available			no sample available			5	47	0.11	5	16	0.31	4	27	0.14
Gabbrodiorite 5	Cu Zn Cu/Zn	6	43	0.12	no sample available			no sample available			no sample available			no sample available			2	38	0.05
Granodiorite 6	Cu Zn Cu/Zn	5	44	0.14	3	15	0.23	no sample available			9	110	0.08	5	20	0.25	4	20	0.20
Granodiorite H.	Cu Zn Cu/Zn	5	40	0.14	2	15	0.13	5	18	0.28	10	78	0.13	7	37	0.18	4	40	0.10
Andesite J.T.1.N.	Cu Zn Cu/Zn	5	40	0.12	5	13	0.38	2	40	0.05	7	64	0.11	9	29	0.31	not collected		
Andesite J.T.1.S.	Cu Zn Cu/Zn	2	19	0.11	4	6	0.66	no sample available			8	47	0.17	9	33	0.27	4	20	0.20
Andesite J.T.3	Cu Zn Cu/Zn	5	28	0.18	no sample available			no sample available			13	28	0.46	11	25	0.44	not collected		

ples numbered J.T.3 and the several K.8 samples to which reference has just been made, all the samples are negative. Great care was taken to collect samples growing under as nearly identical conditions as possible. Except over the shale and the glacial drift itself, all the samples were taken from trees growing virtually on the country rock and nourished only by that rock, a small amount of what was taken to be residual weathered rock, and, of course, the usual forest litter. Wherever possible, sites were chosen where there was little or no chance of contamination by downward circulating waters. The willow and alder from J.T.3 were notable exceptions. They could not be found growing immediately adjacent to the Douglas fir, so they were collected from a little nearby gully, with the results we have already mentioned.

Precise weather records are not available, but all the samples were taken from an area noted for being mild and rainy in winter, and warm, pleasant, and moderately dry during the summer months. The rainfall averages about 40 inches annually. The samples were taken in February on Vancouver Island, just before the deciduous trees commenced to bloom, and on the mainland in March, when the deciduous trees were likewise about to bloom.

By reading horizontally, it is possible to see the different behavior of various species under virtually identical conditions of growth. By reading vertically, it is possible to see something of the normal variations which may be expected in the twigs of one species growing in similar climatic conditions but underlaid by varying rocks.

It is interesting to observe, although the coincidence may be fortuitous, that the samples taken over glacial drift—it was "hard pan" and no roots penetrated it—are just about average for the samples as a whole. As, up to a point, glacial drift normally represents a gigantic mix of all the rocks in an area, perhaps this was to be expected. Some of the results in Table 8 have appeared elsewhere in this paper. They appear again so that the reader may better visualize this aspect of our problem, namely, that different species absorb different and varying amounts of these elements.

THE SELECTION OF SUITABLE ANALYTICAL METHODS

This problem is one which probably has many answers, depending on the degree of accuracy required and whether the analyses are to be carried on in a laboratory, in a well-equipped base camp, or in a rough advance camp. As has already been stated, our work has all been directed towards giving an engineer prospector some tools which will give him an advantage over a pick, shovel, and pan prospector. Remembering the limitations of pack horses and considering the frailties of human nature, we have, up to the present, come to the conclusion that for both copper and zinc the most satisfactory method of analysis is that known as the Dithizone "neutral-mixed-color-end-point" method. Our experience, yet to be substantiated by other workers, suggests that on one- and two-gram samples of young twigs, an accuracy of 5 percent can be achieved, and that even with relatively crude methods a 25 percent to 35 percent accuracy can be obtained by willing and competent workers.

As we have just described this method in another paper to be published in the *Bulletin of The Geological Society of America*, it is not necessary to repeat a description of our procedure here.

However, it will obviously be advisable to do much control work, often of a more precise nature. For those who are interested in more precise methods, a paper by Mitchell[7] should prove of interest. Anybody wanting to check high copper determinations and not demanding greater than about 5 percent to 10

[7] R. L. Mitchell, "Trace Constituents in Soils and Plants: Their Significance and Spectrographic Determination," *Research*, 1, 4 (1948), 159–164.

percent accuracy might well consider the electrolytic method evolved by Delavault and described in the paper referred to in the preceding paragraph.

Indirect Use of Biogeochemistry.—In an earlier paper (Warren and Thompson) reference was made to pathfinders. Pathfinder minerals or elements are those which, while they themselves may have no intrinsic value in the conditions under consideration, may yet be of value in indicating or even determining the presence near by of other valuable minerals or elements.

Boron, manganese, magnesium, and possibly other elements are frequently found in auras around ore bodies. In British Columbia there are mining camps where gold is closely associated with sphalerite, and the finding of sphalerite is almost synonymous with the finding of gold. In an area of this kind, it might be well to prospect biogeochemically for zinc rather than for gold.

Manganese is so widespread in some rocks that its use as a pathfinder element is apt to be restricted. However, at the Sullivan mine, where the sphalerite is highly manganiferous and the surrounding country rock is relatively low in manganese, the authors have shown that there is a correlation between manganese and zinc. In other areas we have not been able to establish such a correlation.

Boron was also investigated at the Sullivan mine. Here a black chert which is closely associated with the ore in some parts of the mine is known to be tourmalinized and carries over 1 percent B. Again an investigation, albeit a little superficial, revealed a surprising correlation between the zinc and boron contents of the willow and lodgepole pine in that area.

Thus, there are by good fortune several elements, such as manganese, boron, and magnesium, which are vital to plant life and which may be associated with ore. Nature herself seems to be offering us clues for finding her frequently all-too-well-hidden storehouses of wealth.

CONCLUSIONS

1. Each plant and each plant organ tends to possess a "normal" content of copper and zinc and to exhibit a "normal" copper-to-zinc ratio. This ratio may be modified by significant variations in the geology or geography of an area. It may also be modified, sometimes to a conspicuous extent, by the presence near by of copper or zinc mineralization.

2. Having determined the "normals" for a given plant organ under the appropriate conditions, it is possible to discover and plot anomalies. These anomalies may be of value in the search for hidden ore bodies.

3. Much more work must be done before normals can even be indicated for different areas. Under good conditions the authors have been able to map anomalies as much as several hundred feet away from known mineralization, and through overburden ranging from 10 to 40 feet.

4. In practice, the authors have found that it is not possible to choose a particular species of tree or lesser plant with which to work. It has been necessary to use what was available. Obviously species which are of widespread occurrence

and which have deep root systems are particularly suitable. We have found willow to be eminently suitable in some areas.

5. Biogeochemical methods may also indicate, in suitable areas, elements such as boron, manganese, or magnesium which may be associated with, or form "haloes" around, ore bodies.

6. Taking all factors into consideration, young twigs provide the most satisfactory samples from trees or lesser plants.

7. Up to the present the most satisfactory analytical method, which may be adapted for use in the field for both copper and zinc, is that known as the Dithizone "neutral-mixed-color-end-point" method.

ACKNOWLEDGMENTS

Many persons have contributed either directly or indirectly to the results presented in this paper. To all of them the authors are deeply obligated. At the risk of making unintentional but none the less invidious distinctions, we must thank the following by name for their assistance: R. W. Diamond, C. O. Swanson, H. R. Banks, H. T. James, C. Cox, C. Riley, C. P. Browning, W. T. Irvine, A. F. Killin, W. I. Nelson, A. B. Staples, F. A. McGonigle, and V. Dolmage of the several mining companies who cooperated; J. Davidson, D. G. Laird, V. C. Brink, G. Shrum, W. F. Seyer, and our own departmental colleagues of the Faculty of the University of British Columbia; H. E. Hawkes, M. F. Fleischer and W. H. Bradley of the United States Geological Survey. In their work the authors were assisted by Rod Williams, Charlie Howatson, J. W. Warden and Ruth Irish, whose emoluments bore little relation to the services they rendered.

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PATENTS*

4—ACCELEROMETER

U. S. No. 2,440,605. C. M. Hathaway. Iss. 4/27/48. App. 5/10/45. Assign. Hathaway Instrument Co.

Accelerometer. An oil-damped accelerometer or vibrometer having a mass suspended on a diaphragm and a pair of coils above and below the mass whose impedances change with displacement of the mass.

U. S. No. 2,441,162. A. E. McPherson. Iss. 5/11/48. App. 8/6/45.

Device for Recording Acceleration in Planes. A mechanically recording accelerometer for measuring crash landing accelerations and having a mass suspended by a cantilever spring which is biased against a stop.

12—ACOUSTIC MEASUREMENTS

U. S. No. 2,443,471. W. P. Mason. Iss. 6/15/48. App. 3/29/45. Assign. Bell Telephone Laboratories, Inc.

Piezoelectric Damping Means for Mechanical Vibrations. An arrangement for damping undesired modes of vibration in a mechanical wave-filter element by applying piezoelectric plates to opposite sides of the element and connecting an electrical impedance between the plates, the plates being poled so that their voltages are aiding for the undesired mode and opposing for the other modes.

16—AIRPLANE FLIGHT INSTRUMENTS

U. S. No. 2,441,381. E. P. Anderson. Iss. 5/11/48. App. 11/27/43. Assign. Bendix Aviation Corp.

Air Log. An air-speed indicator in which a compressor is driven at a rate so that its discharge pressure is balanced against an impact pressure source outside the aircraft so that the compressor speed indicates the air speed.

U. S. No. 2,442, 032. H. T. Booth. Iss. 5/25/48. App. 8/17/44. Assign. United Aircraft Products, Inc.

Viscosity Measuring Instruments. A device for automatically introducing the proper amount of fuel as a diluent to the oil of an engine before shutting it down so that it may easily be restarted when cold.

U. S. No. 2,442,765. C. S. Franklin. Iss. 6/8/48. App. 2/5/46.

Ground Speed Indicator. A device for indicating ground speed when flying a test course having two a-c excited loops a known distance apart, the signal from the first loop being used to start a timer and the signal from the second loop to stop the timer.

U. S. No. 2,443,240. F. H. Hagner. Iss. 6/15/48. App. 5/17/43. Assign Position Finder Corp.

Plotting and Measuring Device. A hemispherical form with a graduated arch over its surface carrying a marker for plotting the course of an airplane.

U. S. No. 2,444,171. R. C. Sanders, Jr. Iss. 6/29/48. App. 7/26/44. Assign. Radio Corp. of America.

Aircraft Navigation. A target-seeking steering system having a radio-sighting device to actuate a steering control through a servomotor and a distance determining device to control the speed of response of the servomotor as a function of distance to the target.

* Abstracts by O. F. Ritzmann, Gulf Oil Corporation.

40—CABLE

U. S. No. 2,442,785. M. M. Shapiro and B. Stiller. Iss. 6/8/48. App. 2/14/44.

Signal-Transmitting Cable Insensitive to Explosion Pressure Pulses. A pressure-insensitive cable for a piezoelectric explosion pressure gage, the cable having a central enameled conductor insulated with fibre glass and embedded in ceresin wax in a larger annealed-copper tube.

108—ECHO SOUNDING

U. S. No. 2,440,248. W. L. Dawson. Iss. 4/27/48. App. 8/19/44 and 12/20/46. Assign. Bell Telephone Laboratories, Inc.

Object Locating Apparatus. A system for compensating an echo-sounding indication for relative motion of the observer by radiating a different frequency between pulses and using its change in frequency to control a compensator.

U. S. No. 2,443,647. C. H. Waterman. Iss. 6/22/48. App. 8/31/44. Assign. Submarine Signal Co.

Electrical Apparatus. An avc circuit for echo-sounding apparatus which prevents strong signals from burning the electro-sensitive recording paper.

124—ELECTRICAL PROSPECTING

U. S. No. 2,440,693. F. W. Lee. Iss. 5/4/48. App. 5/29/42.

Method for Determining the Subterranean Extension of Geologic Bodies. A method of making four-electrode resistivity or impedisivity measurements using also a center potential contact to the formation in a well and observing the potentials on both sides of the center electrode as the surface electrode configuration is rotated in azimuth.

132—ELECTROMAGNETIC PROSPECTING

U. S. No. 2,442,805. W. E. Gibson. Iss. 6/8/48. App. 2/26/45. Assign. The Burdick Corp.

Metal Locator. A surgical probe having at its tip a coil which is the inductance in a high-frequency oscillator circuit, the oscillator being heterodyned with another oscillator and change of beat note used to detect metal bodies.

136—EXPLOSIVE

U. S. No. 2,441,397. L. B. Counterman. Iss. 5/11/48. App. 2/4/43. Assign. Hercules Powder Co.

Explosive Cartridge. A dynamite cartridge having a band around the top through which a suspension cord may be passed and secured in a notch in the band.

140—FLAW DETECTOR

U. S. No. 2,439,130. F. A. Firestone. Iss. 4/6/48. App. 11/20/43. Assign. United Aircraft Corp.

Surface- and Shear-Wave Method and Apparatus. A method of supersonic testing materials for mechanical flaws by observing the travel of either surface waves or shear waves through the material, the waves being generated with specially cut piezo-crystals in contact with the surface.

U. S. No. 2,439,131. F. A. Firestone. Iss. 4/6/48. App. 11/20/43. Assign. United Aircraft Corp.

Resonance Inspection Method. A method of measuring the wall thickness of a hollow airplane propeller by applying a piezoelectric crystal excited with a pulse of varying frequency and observing the frequency of the resonant standing waves after the end of the pulse.

U. S. No. 2,439,184. E. G. Parvin. Iss. 4/6/48. App. 1/23/43. Assign. National Pneumatic Co.

Magnetic Flaw Detector. A machine for testing shell casings by passing a current through them while under pressure and afterward exploring the surface for magnetic variations.

U. S. No. 2,442,393. B. A. Andrews. Iss. 6/1/48. App. 10/4/43. Assign. C. E. Hovey.

Magnetic Testing Means. A flaw detector in which the article and a standard are simultaneously moved through two coils connected in an a-c bridge circuit.

148—FLOW METER

U. S. No. 2,439,121. S. L. Adelson. Iss. 4/6/48. App. 11/26/45. Assign. Infilco, Inc.

Rate of Flow Telemetering Actuator. A telemetering flow meter for actuating a chemical feeder, the pressure differential across a Venturi being used to vary the proportion of on-off time of a motor-driven contactor.

U. S. No. 2,439,614. M. E. Schramm. Iss. 4/13/48. App. 1/11/45. Assign. Shell Development Co.

Flow-Ratio Meter. A rotameter-type flow-ratio meter having concentric tubes with one fluid flowing through the inner tube and the other fluid through the annular space around it, the inner tube having a rotameter float whose position is read on a scale carried on a transparent annular rotameter float in the outer tube.

U. S. No. 2,439,723. R. B. Engdahl. Iss. 4/13/48. App. 1/12/46. Assign. Bituminous Coal Research, Inc.

Flowmeter. A system for measuring the weight rate of flow of solid in a solid-fluid mixture by having in series in the conduit an elongated restriction and also an orifice, measuring the pressure drop across each and from them computing the flow.

U. S. No. 2,441,350. K. Fischer. Iss. 5/11/48. App. 5/15/44. Assign. Fischer & Porter Co.

Rotameter and Metering Tube Therefor. A rotameter-type flow meter in which the tapered rotameter tube has inwardly protruding beads whose tips lie on a cylindrical surface to guide the metering float.

160—GALVANOMETER

U. S. No. 2,439,576. M. E. Morrow. Iss. 4/13/48. App. 8/20/45. Assign. Century Geophysical Corp.

Galvanometer Movable Coil Support. A barrel-type oscillograph galvanometer in which the coil element is anchored on end closures both of which are insertable from one end of the barrel.

U. S. No. 2,442,355. G. R. Greenslade. Iss. 6/1/48. App. 9/6/44. Assign. Flannery Bolt Co.

Galvanometer Mounting. A vibration-proof mounting for a portable sensitive galvanometer, the instrument being mounted on a heavy base suspended in a carrying case by damped springs and having manually operated clamps to prevent swaying in transit.

U. S. No. 2,442,741. J. D. Morgan and R. E. Lowe. Iss. 6/1/48. App. 9/6/45. Assign. Cities Service Oil Co.

High Viscosity Damping Fluid. A low-temperature damping fluid for use in dash-pots and made of 50 percent tri-octyl-phosphate and 50 percent of a mixture of octyl-decyl esters of methacrylic acid polymerized to a molecular weight of about 10,000.

168—GAS ANALYSIS

U. S. No. 2,443,427. R. E. Kidder and J. W. Berry. Iss. 6/15/48. App. 8/29/44. Assign. American Cyanamid Co.

Infrared Gas Analyzer. An infrared absorption analyzer in which a beam is passed through a sample cell and gas cell in succession, and a second beam is passed through a standard comparison cell and through another similar gas cell, the temperature difference between the gas cells being observed with a differential manometer and photoelectrically recorded.

172—GEOCHEMICAL PROSPECTING

U. S. No. 2,442,476. M. S. Taggart, Jr. Iss. 6/1/48. App. 9/10/46. Assign. Standard Oil Development Co.

Prospecting for Petroleum Deposits. A method of geochemical prospecting in which soil samples are taken at uniform depth, the sample mixed with an electrolyte and an electrode inserted and the oxidation-reduction potential measured against a standard half-cell.

180—GRAVIMETER

U. S. No. 2,441,166. A. Raspet. Iss. 5/11/48. App. 3/27/42 and 6/7/46.

Helical Spring. A helical spring having a pitch angle for which the rotary magnification expressed as turns of the spring per unit elongation is constant.

U. S. No. 2,441,167. A. Raspet. Iss. 5/11/48. App. 3/27/42 and 6/7/46.

Helical Spring. A helical spring in which the helix angle is so selected that the rotary magnification expressed as turns of the spring per unit elongation is directly proportional to its length.

188—HYGROMETER

U. S. No. 2,444,111. C. B. Pear, Jr. Iss. 6/29/48. App. 6/15/45. Assign. Washington Institute of Technology, Inc.

System for Improving Operation of Electrical Hygrometers in Radiosondes. A circuit which prevents deterioration of the humidity-sensitive film of a hygrometer by passing reverse current through it during the intervals when a hygrometer reading is not taken.

192—INCLINOMETER

U. S. No. 2,444,265. F. C. Ostheimer. Iss. 6/29/48. App. 8/9/45.

Inclinometer. A liquid-type inclinometer having a series of radially spaced open-ended small bore tubes connected to a liquid reservoir and a closure valve which closes the top of the tubes when a reading is taken, the inclination being determined by differences in liquid height in the tubes.

216—MAGNETIC COMPASS

U. S. No. 2,441,269. H. E. Hartig. Iss. 5/11/48. App. 5/31/43. Assign. Minneapolis-Honeywell Regulator Co.

Electron Discharge Compass System. A cathode-ray tube compass in which a beam of modulated intensity falls on the two sides of a split target connected to an a-c amplifier which drives an orienting motor.

U. S. No. 2,443,595. F. D. Braddon. Iss. 6/22/48. App. 1/22/43. Assign. The Sperry Corp.

Deviation Correcting Means for Magnetic Devices. A system for correcting a compass for deviations caused by temporary operation of electrical equipment by using Helmholtz coils energized to correct the permanent deviations and connected so that the coil current is changed by the proper amount when the electrical equipment is turned on.

U. S. No. 2,444,290. C. E. Granqvist. Iss. 6/29/48. App. 2/2/43 and 11/27/43. Assign. Svenska Aktiebolaget Gasaccumulator.

Earth Induction Compass. An inductor compass in which the cores are subjected to an a-c field from a polarizing coil so that the induced voltage represents the polarizing field modulated by the earth's field, the induced current being rectified and indicated on a watt meter which is also connected to the a-c source.

224—MAGNETIC RECORDER

U. S. No. 2,439,446. S. J. Begun. Iss. 4/13/48. App. 11/29/44. Assign. The Brush Development Co.

Control Circuit for Signal Recording and Reproducing Systems. A control for an endless belt magnetic recorder reproducer in which a signal put on the tape cuts off the recording head when it reaches the reproducing head and actuates a counter.

U. S. No. 2,441,065. W. G. Green. Iss. 5/4/48. App. 12/1/45. Assign. Engineering Laboratories. Inc.

Apparatus for Well Logging. A system of well logging in which a magnetizable wire is run into the hole and footage marks magnetically recorded on the wire as it is run in, then a self-contained logging instrument lowered to record magnetically on the wire as it goes down and the composite record played back when the wire is taken out of the hole.

U. S. No. 2,441,679. W. H. Wade. Iss. 5/18/48. App. 5/28/45. Assign. Lear, Inc.

Magnetic Recording Apparatus. A magnetic recorder in which the wire is wound on magazine-type reel having a unidirectional driving clutch.

228—MAGNETIC TESTING

U. S. No. 2,440,575. F. Dedek. Iss. 4/27/48. App. 4/15/44. Assign. Magnetic Products Corp.

Electromagnetic Testing Device. A magnetic testing device having a laminated high-permeability core with legs which may be placed in contact with a specimen to be tested.

U. S. No. 2,440,984. C. M. Summers. Iss. 5/4/48. App. 6/18/45. Assign. General Electric Co.

Magnetic Testing Apparatus and Method. An a-c magnetic testing apparatus having a transformer with two secondaries on separate legs, one secondary energizing the specimen and the other having adjustable resistance and inductance, balance between the two secondaries being indicated on a c-r tube coupled to the two secondary legs of the transformer.

U. S. No. 2,441,380. T. Zuschlag. Iss. 5/11/48. App. 4/8/41 and 11/30/44. Assign. Magnetic Analysis Corp.

Magnetic Analysis. A magnetic tester for irregularities in dimension or surface characteristics of round bar stock in which the material is spiralled past the ends of two cores having center-tapped windings each connected in an a-c bridge circuit whose unbalance is indicated.

U. S. No. 2,442,393. B. A. Andrews. Iss. 6/1/48. App. 10/4/43. Assign. C. E. Hovey.

Magnetic Testing Means. A flaw detector in which the article and a standard are simultaneously moved through two coils connected in an a-c bridge circuit.

232—MAGNETOMETER

U. S. No. 2,438,964. D. H. Cunningham and H. Belar. Iss. 4/6/48. App. 11/2/42. Assign. Radio Corp. of America.

Magnetic Field Detector. A magnetometer having three mutually perpendicular cores with primary windings excited from three a-c sources and with secondary windings whose outputs are separately filtered and the even harmonics fed into separate square-law detectors whose outputs are individually indicated and also algebraically added and indicated.

U. S. No. 2,440,503. C. H. Fay. Iss. 4/27/48. App. 1/11/45. Assign. Shell Development Co.

Magnetic Gradiometer. A magnetic gradiometer having two elastically suspended coils each carrying a mirror which reflects a beam of light onto a photocell whose output is amplified and fed back to the respective coil to sustain oscillation and also having a rectifier connected to the amplifier output

and supplying Helmholtz coils which neutralize the ambient field, the gradient being measured by the difference in the outputs of the two oscillating systems.

U. S. No. 2,442,732. J. H. Rubenstein. Iss. 6/1/48. App. 4/16/45.

Magnetometer. A mechanical-attraction pointer-type magnetometer having two high-permeability magnetic arms to concentrate the flux, the sensitivity being adjusted by varying the gap between the arms or by exposing the arms to two permanent magnets to change their operating permeability.

244—MICROPHONE

U. S. No. 2,444,049. J. H. King. Iss. 6/29/48. App. 1/26/45. Assign. Bell Telephone Laboratories, Inc.

Pressure-Compensated Submarine Sound Transmitter or Receiver. A pressure-compensating system for a hydrophone in which gas from a pressure tank is fed into the hydrophone chamber by a valve controlled by a float in an auxiliary equilibrium chamber.

276—PERMEABILITY TESTING

U. S. No. 2,443,680. G. Herzog. Iss. 6/22/48. App. 4/4/44. Assign. The Texas Co.

Method of Determining the Nature of Substrata. A method of determining formation permeability by bombarding the formation with neutrons and at the same time forcing into the formation a substance which emits gamma rays when bombarded by neutrons so that the progress of the substance into the formation may be observed with a radioactivity detector.

288—PRESSURE GAGE

U. S. No. 2,439,047. C. E. Grinstead and R. N. Frawley. Iss. 4/6/48. App. 5/27/44. Assign. General Motors Corp.

Pressure Indicator. A cylinder pressure gage for an internal-combustion engine in which the pressure varies the capacity of a condenser connected to a transformer whose secondary is connected to an indicating circuit.

U. S. No. 2,439,092. F. T. Linstrom. Iss. 4/6/48. App. 9/26/46. Assign. one-third to G. B. Waldron and one-third to C. H. Callison.

Apparatus for Indicating Pressure at a Distance. An electrically indicating pressure gage having a diaphragm of insulating material with a spiral of resistance wire cemented to its surface, the diaphragm and wire being forced against a convex contactor to vary the resistance in circuit.

U. S. No. 2,439,342. W. J. Hudson. Iss. 4/6/48. App. 2/23/44.

Pressure Measuring Apparatus. A liquid barometer having a Cartesian diver whose vertical position is indicated.

U. S. No. 2,439,770. H. A. Brown and H. Gollob. Iss. 4/13/48. App. 1/29/45.

Electrically Indicating Liquid Filled Manometer. A manometer tube having a resistance rod down the center and using a conducting liquid which changes the length of rod in the circuit.

U. S. No. 2,440,704. P. L. Spencer. Iss. 5/4/48. App. 2/26/44. Assign. Raytheon Manufacturing Co.

Pressure Measuring Device. A temperature-compensated Aneroid barometer having a closed elastic chamber connected to a differential pressure gage, the walls of the chamber having a bimetallic helix which changes its volume to correct for temperature variations.

U. S. No. 2,442,938. A. C. Ruge. Iss. 6/8/48. App. 9/13/45. Assign. The Baldwin Locomotive Works.

Fluid Pressure Responsive Apparatus. An electrical pressure gage in which the pressure is applied

to an Sylphon bellows which deflects a cantilever beam having filament-type strain gages mounted on its sides.

U. S. No. 2,443,252. F. G. Kelly. Iss. 6/15/48. App. 11/2/44. Assign. Thomas A. Edison, Inc.

Pressure Operated Rheostat. A fluid pressure indicator having a bellows which actuates the contact arm of a rheostat.

304—RADIOACTIVITY LOGGING

U. S. No. 2,443,680. G. Herzog. Iss. 6/22/48. App. 4/4/44. Assign. The Texas Co.

Method of Determining the Nature of Substrata. A method of determining formation permeability by bombarding the formation with neutrons and at the same time forcing into the formation a substance which emits gamma rays when bombarded by neutrons so that the progress of the substance into the formation may be observed with a radioactivity detector.

U. S. No. 2,443,731. G. Herzog and K. C. Crumrine. Iss. 6/22/48. App. 11/27/43. Assign. The Texas Co.

Method and Apparatus for Logging Boreholes. A method of neutron logging in which a source of fast neutrons is used surrounded by a detector sensitive only to slow neutrons so as to minimize the effect of the primary neutrons and detect only scattered neutrons.

308—RADIOACTIVITY MEASUREMENTS

U. S. No. 2,440,167. J. W. Broxon and W. P. Jesse. Iss. 4/20/48. App. 1/20/44. Assign. U.S.A.

Differential Ion Chamber. A detector for slow neutrons in which the effect of gamma rays and fast neutrons is cancelled by using concentric chambers only one of which has a material which gives off alpha particles when bombarded by slow neutrons and indicating the difference in ion currents.

U. S. No. 2,440,511. D. G. C. Hare. Iss. 4/27/48. App. 12/29/44. Assign. Texaco Development Corp.

Radiation Detector. A gamma-ray detector made up of a series of cathode discs or truncated cones with a central anode wire.

U. S. No. 2,440,999. H. L. Anderson. Iss. 5/4/48. App. 7/1/43. Assign. U.S.A.

Compressed Neutron Source. A neutron source made by mixing a radium salt with beryllium powder and compressing the mixture to form a cylindrical pellet whose length is equal to its diameter and enclosing the pellet in a metal case.

U. S. No. 2,442,314. A. F. Reid. Iss. 5/25/48. App. 7/17/45. Assign. U.S.A.

Geiger Counter Improvement. A Geiger counter using as a quenching gas an alkyl mono-halide of two to six carbon atoms.

U. S. No. 2,442,617. S. Rosenblum. Iss. 6/1/48. App. 10/31/42. Assign. Canadian Radium & Uranium Corp.

Carrier for Radioactive Material and Improved Method of Making the Same. A method of incorporating radioactive material in the wall of a glass container or carrier by depositing a thin film of the radioactive material on the surface, heating the glass to impart electrical conductivity and passing a current through the wall of the container.

U. S. No. 2,443,365. E. H. Wakefield. Iss. 6/15/48. App. 12/11/45. Assign. U.S.A.

Support for Geiger-Mueller Counters. A mounting which holds a Geiger-Mueller tube and its high voltage lead to prevent tension on the seals and permits removing and replacing the unit in a shield.

U. S. No. 2,443,591. E. Banks and J. Bland. Iss. 6/22/48. App. 6/7/45.

Radium Holder. A radium holder for radiographing high-pressure pipe welds having a strap which clamps around the pipe and an adjustable arm clamped to the strap with thumb screws.

U. S. No. 2,443,857. G. Herzog. Iss. 6/22/48. App. 4/24/45. Assign. The Texas Co.

Circuit for the Control of Radiation Detectors. A circuit for controlling the voltage on a counter-type radiation detector by having a vacuum tube in parallel with the detector and deriving from the detector circuit a negative bias which is proportional to the pulse-counting rate and which is applied to the grid of the parallel tube to vary its current inversely as the counting rate.

312—RADIO NAVIGATION

U. S. No. 2,438,987. C. E. G. Bailey. Iss. 4/6/48. App. 9/13/45. Assign. Radio Transmission Equipment, Ltd.

Radio Navigational Aid. A pulse-type of radio navigation system in which pulses are radiated at slightly different directions and with one pulse shorter and inside of the other so that the reflected pulse annuls first the short-pulse output and then the long-pulse output on the c-r tube screen.

U. S. No. 2,439,663. H. M. Lewis. Iss. 4/13/48. App. 2/26/42. Assign. Hazeltine Research, Inc.

System for Navigating Aircraft. A radio blind-landing system using two elevated antenna systems radiating frequency modulated carriers and detecting on the plane the difference frequency between the direct wave and the wave reflected from the ground from each antenna.

U. S. No. 2,439,846. O. H. Dicke. Iss. 4/20/48. App. 4/21/44. Assign. General Railway Signal Co.

Airplane Course-Indicating System. An airplane course-indicating system having a series of high-frequency radio ground stations and scanning apparatus on the plane indicating the position of the ground stations in perspective on the screen of a c-r tube.

U. S. No. 2,440,755. W. J. O'Brien. Iss. 5/4/48. App. 8/27/45. Assign. The Decca Record Co., Ltd.

Radio-Frequency Navigation System. A phase-comparison system of radio navigation using three spaced stations radiating simultaneously, the middle station radiating signals of two frequencies and the end stations radiating signals differing by the same amount from one of these.

U. S. No. 2,442,692. P. F. G. Holst and L. R. Kirkwood. Iss. 6/1/48. App. 7/10/46. Assign. Radio Corp. of America.

Radio Navigation System. A system in which recurring pulses are transmitted from two synchronized ground stations and the difference in reception times observed on a c-r tube screen by moving a marker pulse from one received pulse to the other.

U. S. No. 2,444,171. R. C. Sanders, Jr. Iss. 6/29/48. App. 7/26/44. Assign. Radio Corp. of America.

Aircraft Navigation. A target-seeking steering system having a radio sighting device to actuate a steering control through a servomotor and a distance determining device to control the speed of response of the servomotor as a function of distance to the target.

316—RADIO RANGING

U. S. No. 2,438,946. A. G. Richardson, F. O. Chesus and F. G. Thomas. Iss. 4/6/48. App. 2/20/43. Assign. Federal Telephone and Radio Corp.

Radio Direction Finding System. A type of rotating-antenna radio direction finder which indicates bearing on a c-r tube screen and which has a circuit for producing pulses at a predetermined angular position of the rotating antenna.

U. S. No. 2,440,250. E. M. Deloraine, E. Labin and P. F. M. Gloess. Iss. 4/27/48. App. 4/4/40 and 6/3/43. Assign. International Standard Electric Corp.

Radio Location System. A radar system having one radiator and two spaced receivers which indicate the position of the reflector on a c-r tube screen at a central station.

U. S. No. 2,440,268. R. Hardy. Iss. 4/27/48. App. 1/17/41 and 5/28/43. Assign. International Standard Electric Corp.

Electromagnetic Wave Direction Indicator. A rotating-loop-type radio direction finder in which 180° ambiguity is eliminated by having a signal from a vertical antenna block the indicator through a synchronously rotating commutator on the wrong side of the loop.

U. S. No. 2,440,682. P. G. Hansel. Iss. 5/4/48. App. 3/3/45.

Radio Direction Finder. A radio direction finder in which the signal from the last i-f stage is impressed on a diode detector stage feeding a bridge circuit whose arms have R-C circuits of different time constants, with the bridge actuating a trigger circuit which actuates the direction indicator only on a signal above a predetermined threshold.

U. S. No. 2,440,777. J. Lyman. Iss. 5/4/48. App. 4/13/48 and 1/31/46. Assign. The Sperry Corp.

Tridimensional Radio Direction Indicator. A radar system in which two sets of antennas have their reception patterns varied to scan a field both in azimuth and elevation and whose signals control trigger circuits so as to indicate on the screen of a c-r tube whose beam is deflected in synchronism with the scanning.

U. S. No. 2,441,658. E. D. Blodgett and D. S. Bond. Iss. 5/18/48. App. 3/30/45. Assign. Radio Corp. of America.

Direction Finder. A radio direction finder whose antenna has a single-lobed pattern which is cyclically varied in direction and the received voltage indicated on a synchronously rotating spot on a c-r tube screen.

U. S. No. 2,443,718. E. D. Blodgett. Iss. 6/22/48. App. 3/28/45. Assign. Radio Corp. of America.

Direction Finder. A radar system using an antenna whose pattern has one sharply defined null which is scanned over an arc and whose signal is indicated on a c-r tube.

U. S. No. 2,444,031. H. G. Busignies. Iss. 6/29/48. App. 3/18/41. Assign. International Standard Electric Corp.

Electromagnetic-Wave Obstacle Detection System. A radar system in which a transmitted energy pattern is continuously oscillated between two angular positions and signals from a non-directional receiver indicated on a c-r tube whose beam is deflected in synchronism with the transmitted pattern.

U. S. No. 2,444,388. D. De Vries. Iss. 6/27/48. App. 3/18/38 and 12/29/38. Assign. Hartford National Bank and Trust Co.

Device for Indicating Direction and Distance. A radar system in which two sets of varying-frequency pulses are transmitted and combined with the received reflections and the combined current indicated on a c-r tube.

324—RECORDER

U. S. No. 2,440,841. K. De Boer. Iss. 5/4/48. App. 3/29/41 and 1/29/43. Assign. Hartford National Bank and Trust Co.

Device for Mechanically Recording Sound in Two Tracks. An arrangement of two cutting heads for mechanically recording on a tape, one head being located between the drum and the base plate, and one above the drum and with their styli close together.

364—SEISMOGRAPH RECORDER

U. S. No. 2,440,970. E. M. Palmer. Iss. 5/4/48. App. 6/14/45 and 1/15/48. Assign. Gulf Research & Development Co.

Seismograph Recording Apparatus. A mechanical device having a cone-shaped cam with followers which longitudinally shift the recording elements in a multi-channel seismograph recorder so that reflected events fall in a straight line across the tape.

U. S. No. 2,440,971. E. M. Palmer. Iss. 5/4/48. App. 6/14/45. Assign. Gulf Research & Development Co.

Seismograph Recording Apparatus. A mechanical device having cams driven with the recording tape for longitudinally shifting the recording elements in a multi-channel seismograph so that recorded reflected seismic events fall in a straight line across the tape.

416—SPECTROGRAPH

U. S. No. 2,442,098. C. T. Shewell and J. R. Shewell. Iss. 5/25/48. App. 11/13/45. Assign. Standard Oil Development Co.

Apparatus for Interpretation of Spectrum Analysis Data Represented by a Curve. A mechanical device for simultaneously manually tracing two curves and having a system of linkage which operates a stylus which draws a difference curve.

420—SPECTROPHOTOMETER

U. S. No. 2,439,373. E. I. Stearns, Jr. Iss. 4/6/48. App. 9/27/44. Assign. American Cyanamid Co.

Flickering Beam Photometer. A flickering beam photometer in which the light from a source is split into two beams and each put through a filter corresponding to an absorption band of a component of material placed in the path of the beams and the two beams alternately permitted to fall on a radiation detector.

428—STRAIN GAGE

U. S. No. 2,440,706. L. M. Tint. Iss. 5/4/48. App. 8/18/45.

Strain Gage Assembly. A strain gage having a ring with diametrically opposed extensions to which the strain is applied and having filament-type electric strain gages mounted on the inside and outside of the semicircular parts of the ring between the extensions.

U. S. No. 2,443,045. P. M. Magruder and W. W. Bender, Jr. Iss. 6/8/48. App. 3/9/44. Assign. Glenn L. Martin Co.

Strain Gage Center of Gravity and Gross Weight Meter. A system for determining gross weight and center of gravity of an airplane having tricycle landing gear by applying temperature compensated strain gages to the landing gear struts and connected to a bridge-type circuit indicating the parameters on meters.

U. S. No. 2,443,661. B. E. Lenehan. Iss. 6/22/48. App. 8/10/44. Assign. Westinghouse Electric Corp.

Gage System for Measuring Small Variations in Dimensions. A thickness or strain gage of the variable-air-gap impedance-bridge type in which the energizing coil and the pickup coils are connected to a ratiometer so as to compensate for variations in supply voltage.

436—SUBMARINE SIGNALING

U. S. No. 3,438,925. H. K. Krantz. Iss. 4/6/48. App. 8/18/44. Assign. Bell Telephone Laboratories, Inc.

Magnetostrictive Submarine Signal Transmitter or Receiver. A magnetostrictive supersonic sub-

marine signaling receiver or projector in which the radiator is a cylinder of rubber having an annular magnetostrictive core with coil around it to produce radial vibrations which are transmitted from the end of the rubber cylinder to the water.

U. S. No. 2,438,926. E. E. Mott. Iss. 5/6/48. App. 8/18/44. Assign. Bell Telephone Laboratories, Inc.

Magnetostrictive Supersonic Transducer. A supersonic submarine signaling receiver or projector having an annular magnetostrictive core wound with a coil and entirely embedded in a plastic containing finely divided metal particles.

U. S. No. 2,438,936. W. P. Mason. Iss. 4/6/48. App. 10/6/43. Assign. Bell Telephone Laboratories, Inc.

Electromechanical Transducer. A high-power ultrasonic compressional-wave transmitter which produces a wide beam at high frequency and having driving elements cemented to a spherical radiating surface or having a lens-shaped material of high sonic refraction between a flat radiator and the medium.

U. S. No. 2,440,903. F. Massa. Iss. 5/4/48. App. 1/6/44. Assign. The Brush Development Co.

Underwater Transducer. A hydrophone in the form of an underwater streamer made by mounting sound-transparent windows in a long rubber hose filled with oil and with piezoelectric transducers at the windows.

U. S. No. 2,443,177. J. T. Beechlyn. Iss. 6/15/48. App. 2/28/44. Assign. Submarine Signal Co.

Submarine Signaling Apparatus. A magnetostriction compressional-wave receiver or projector made of a number of magnetostrictive tubes suspended to vibrate freely with the exciting wires mounted inside the tubes.

U. S. No. 2,443,178. H. Benioff. Iss. 6/15/48. App. 4/3/41. Assign. Submarine Signal Co.

Piezoelectric Vibrator. A supersonic vibrator having a large radiating plate with vibrating units bolted to the back, each unit having side recesses in which piezoelectric elements are mounted so that their electrodes are on the sides and their vibration axis is longitudinal with the unit.

U. S. No. 2,444,049. J. H. King. Iss. 6/29/48. App. 1/26/45. Assign. Bell Telephone Laboratories, Inc.

Pressure-Compensated Submarine Sound Transmitter or Receiver. A pressure-compensating system for a hydrophone in which gas from a pressure tank is fed into the hydrophone chamber by a valve controlled by a float in an auxiliary equilibrium chamber.

U. S. No. 2,444,069. L. J. Sivian. Iss. 6/29/48. App. 3/2/45. Assign. Bell Telephone Laboratories. Inc.

System for Receiving Sounds in the Presence of Disturbing Noises. A system for receiving underwater sound on a ship in the presence of propeller noise by placing two hydrophones near the propeller, one being a non-directional stiffness-controlled pressure hydrophone and the other a directional mass-controlled pressure-gradient hydrophone and with a phase shift intoduced into the pressure hydrophone so that the difference signal cancels out for the propeller noise.

460—THERMOMETER

U. S. No. 2,442,298. M. D. Liston. Iss. 5/25/48. App. 5/29/44. Assign. General Motors Corp.

Modulated Heat Ray Detector. A heat detector in which the rays are slowly interrupted by a chopper and the thermocouple output is converted to ac, amplified and rectified, then passed through a band-pass filter and finally rectified in synchronism with the chopper and indicated on a d-c meter.

468—TIME INTERVAL METER

U. S. No. 2,438,904. L. A. DeRosa. Iss. 4/6/48. App. 11/23/42. Assign. Federal Telephone and Radio Corp.

Timing System. A timing system for a pulse-echo radio detection system in which an L-C circuit is shock excited and the damped wave applied to a tube whose bias is gradually varied to increase its gain sufficiently to offset the damping of the oscillations.

U. S. No. 2,439,446. S. J. Begun. Iss. 4/13/48. App. 11/29/44. Assign. The Brush Development Co.

Control Circuit for Signal Recording and Reproducing Systems. A control for an endless-belt magnetic recorder-reproducer in which a signal put on the tape cuts off the recording head when it reaches the reproducing head and actuates a counter.

484—TRANSDUCER

U. S. No. 2,438,925. H. K. Krantz. Iss. 4/6/48. App. 8/18/44. Assign. Bell Telephone Laboratories, Inc.

Magnetostrictive Submarine-Signal Transmitter or Receiver. A magnetostrictive supersonic submarine-signalling receiver or projector in which the radiator is a cylinder of rubber having an annular magnetostrictive core with coil around it to produce radial vibrations which are transmitted from the end of the rubber cylinder to the water.

U. S. No. 2,438,926. E. E. Mott. Iss. 4/6/48. App. 8/18/44. Assign. Bell Telephone Laboratories, Inc.

Magnetostrictive Supersonic Transducer. A supersonic submarine signaling receiver or projector having an annular magnetostrictive core wound with a coil and entirely embedded in a plastic containing finely divided metal particles.

U. S. No. 2,438,936. W. P. Mason. Iss. 4/6/48. App. 10/6/43. Assign. Bell Telephone Laboratories, Inc.

Electromechanical Transducer. A high-power ultrasonic compressional-wave transmitter which produces a wide beam at high frequency and having driving elements cemented to a spherical radiating surface or having a lens-shaped material of high sonic refraction between a flat radiator and the medium.

U. S. No. 2,439,219. J. C. O'Connor. Iss. 4/6/48. App. 6/9/44.

Apparatus for Transmitting Intense Vibrations for Performing Work. An electrically driven vibrator having a transversely vibrating beam with a flexible material bonded to the beam and to the support to prevent sliding friction at the clamp.

U. S. No. 2,439,459. W. C. Eddy. Iss. 4/13/48. App. 8/6/45. Assign. Television Associates, Inc.

Sound Pickup Unit. A hearing aid made in the form of a smoking pipe which carries the sound reproducer and transmits the sound to the user by bone conduction through his teeth.

U. S. No. 2,439,499. A. L. W. Williams and W. J. Brown. Iss. 4/13/48. App. 8/20/42. Assign. The Brush Development Co.

Piezoelectric Motor. An array of three or more piezoelectric cyrstal units which are excited by properly arranged polyphase voltages so that the unit effects a gyratory motion of a planetary gear which imparts rotary motion to the internal teeth of a sun gear.

U. S. No. 2,439,711. D. E. Bovey. Iss. 4/13/48. App. 6/14/43. Assign. Woodward Governor Co.

Electrical Measurement of Displacement. A variable-air-gap a-c excited displacement detector for

a remote condition indicator or controller in which two air gaps vary in opposite directions and two a-c secondary currents are rectified and their difference indicated.

U. S. No. 2,440,439. W. E. Gilman. Iss. 4/27/48. App. 7/4/42. Assign. Permoflux Corp.

Permanent-Magnet Electrodynamic Transducer. An earphone for a headset having a permanent magnet and a moving coil which drives the diaphragm.

U. S. No. 2,440,565. J. J. Antalek. Iss. 4/27/48. App. 9/19/44. Assign. The Rauland Corp.

Translating Device. A vibration pickup for converting mechanical into electrical energy by moving an element of a vacuum tube so as to vary the plate current or the width of a beam falling on a fluorescent screen.

U. S. No. 2,440,903. F. Massa. Iss. 5/4/58. App. 1/6/44. Assign. The Brush Development Co.

Underwater Transducer. A hydrophone in the form of an underwater streamer made by mounting sound-transparent windows in a long rubber hose filled with oil and with piezoelectric transducers at the windows.

U. S. No. 2,441,354. L. A. Gould. Iss. 5/11/48. App. 1/17/41. Assign. Maguire Industries, Inc.

Frequency-Modulation Phonograph Pickup System. A phonograph pickup having a local oscillator mounted inside the supporting arm and in which the stylus moves a short-circuited coil in the field of the oscillator inductance to change its tuning.

U. S. No. 2,441,464. R. B. Albright. Iss. 5/11/48. App. 6/13/41. Assign. Philco Corp.

Modulated-Oscillator Phonograph Transducer. A phonograph pickup in which the stylus vibrates a magnetic vane located in the inductance of an oscillator so as to change the Q of the coil and vary the amplitude of oscillation.

U. S. No. 2,441,651. L. Thompson. Iss. 5/18/48. App. 12/27/45. Assign. The Soundscriber Corp.

Phonograph Recording Head. A permanent magnet variable air-gap reluctance type phonograph recorder-reproducer.

U. S. No. 2,443,177. J. T. Beechlyn. Iss. 6/15/48. App. 2/28/44. Assign. Submarine Signal Co.

Submarine Signaling Apparatus. A magnetostriction compressional-wave receiver or projector made of a number of magnetostrictive tubes suspended to vibrate freely with the exciting wires mounted inside the tubes.

U. S. No. 2,443,178. H. Benioff. Iss. 6/15/48. App. 4/3/41. Assign. Submarine Signal Co.

Piezoelectric Vibrator. A supersonic vibrator having a large radiating plate with vibrating units bolted to the back, each unit having side recesses in which piezoelectric elements are mounted so that their electrodes are on the sides and their vibration axis is longitudinal with the units.

U. S. No. 2,444,061. R. L. Peek, Jr. Iss. 6/29/48. App. 5/26/44. Assign. Bell Telephone Laboratories, Inc.

Magnetostrictive Device. A magnetostrictive vibrator made of a longitudinally polarized bar mounted for flexural vibration and having a transverse slot so as to form two arms with the exciting coil threading one of the arms.

U. S. No. 2,444,336. L. B. Cornwell. Iss. 6/29/48. App. 1/30/46.

Electrical Sound Translating Device. A magnetic-type phonograph pickup for lateral-cut records having a permanent magnet and pickup coils on the same polarity side only so as to compensate electrical pickup.

490—VEHICLE

U. S. No. 2,442,032. H. T. Booth. Iss. 5/25/48. App. 8/17/44. Assign. United Aircraft Products, Inc.

Viscosity Measuring Instrument. A device for automatically introducing the proper amount of fuel as a diluent to the oil of an engine before shutting it down so that it may easily be restarted when cold.

492—VIBROMETER

U. S. No. 2,443,969. J. M. Tyler and V. E. Thornburg. Iss. 6/22/48. App. 3/12/46. Assign. United Aircraft Corp.

Vibrating Pickup. A permanent magnet moving-coil type of vibrometer in which the coil is mounted on a spring-suspended pivoted arm and moves in the field of a permanent magnet forming part of the frame.

496—VISCOSIMETER

U. S. No. 2,439,287. L. C. Eitzen. Iss. 4/6/48. App. 3/8/44.

Viscosity Instrument. A falling-ball viscosimeter having two tubes with a standard oil in one and with a nozzle and hand-operated piston in the other so that it may be filled with the sample oil and the rates of fall of the balls compared.

U. S. No. 2,442,032. H. T. Booth. Iss. 5/25/48. App. 8/17/44. Assign. United Aircraft Products, Inc.

Viscosity Measuring Instrument. A device for automatically introducing the proper amount of fuel as a diluent to the oil of an engine before shutting it down so that it may easily be restarted when cold.

508—WATER LOCATING

U. S. No. 2,439,542. R. S. Hunt. Iss. 4/13/48. App. 4/4/45.

Water Detector for Oil Wells. A dye-carrying sleeve which is put around the lowest section of casing before it is set so that leakage past the casing seat may be detected if the dye appears.

516—WELL SIGNALING

U. S. No. 2,441,065. W. G. Green. Iss. 5/4/48. App. 12/1/45. Assign. Engineering Laboratories, Inc.

Apparatus for Well Logging. A system of well logging in which a magnetizable wire is run into the hole and footage marks magnetically recorded on the wire as it is run in, then a self-contained logging instrument lowered to record magnetically on the wire as it goes down and the composite record played back when the wire is taken out of the hole.

520—WELL SURVEYING

U. S. No. 2,441,065. W. G. Green. Iss. 5/4/48. App. 12/1/45. Assign. Engineering Laboratories, Inc.

Apparatus for Well Logging. A system of well logging in which a magnetizable wire is run into the hole and footage marks magnetically recorded on the wire as it is run in, then a self-contained logging instrument lowered to record magnetically on the wire as it goes down and the composite record played back when the wire is taken out of the hole.

REVIEWS

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"Geothermal Gradients, Recent Climatic Changes, and Rate of Sulfide Oxidation in the San Manuel District, Arizona," by T. S. Lovering. *Economic Geology*, XLIII (January–February, 1948). Pp. 1–20.

The author made measurements in 11 holes using Van Orstrand's maximum-thermometer method at depths between 100 and 1,000 feet. Thermal conductivities were determined by Birch on three representative samples of the rocks penetrated. From his thermal data and the conductivity data, the author computes that the upward heat flow is at the rate of 30 to 46 calories per square centimeter per year, which is in good agreement with the results obtained in other areas. There are various changes in gradient, some of which cannot be explained as changes in the rock conductivity. Historical records and Douglas' data on tree rings show that this area had a relatively humid climate up to about 65 years ago at which time the present drought conditions began. The author assumes that this change in weather conditions caused an increase in surface temperature except in arroyos where the ground is not exposed to the sun during all the daylight hours. He assumes that the surface was at a uniform temperature of 71° F. during the humid period prior to 1880, and then using this surface temperature, Birch's values of conductivity, his own values of diffusivity and his measured temperatures he computes the temperature gradients which might have existed prior to 1880. These computed gradients are more uniform than those measured for all holes, and his theory is certainly an interesting way of explaining some rather sharp breaks which he gets in some of his temperature curves in the neighborhood of 300 or 400 feet. The tree-ring records also indicate a similar change in climatic conditions from about 1,570 to 1,600. Some of the thermal data show breaks at 800 or 900 feet which might possibly reflect different climatic changes but, as he points out, there are insufficient data for more than very tentative conclusions on this point.

All of the holes penetrate rocks containing pyrite. In two of the holes, these beds are above the water table, and the temperature curves show breaks which can best be explained by assuming these beds are giving off heat because of oxidation of the pyrite to limonite. The other pyrite beds, which are below the water table, do not show such sharp breaks. The author computes that it would take approximately 1,600,000 years to complete the oxidation of the pyritiferous beds using only oxygen brought to the bed in saturated water solution with a rainfall of 10 inches per year. However, to support the change in gradient, the oxidation would have to be completed in 40,000 years. The author assumes, therefore, that about 95 percent of the oxygen consumed in the reaction reaches the formation by breathing caused by changes in barometric pressure. This conclusion is in accordance with data in other areas in which thermal highs of 10° to 40° F. above normal rock temperature are found in association with such pyrite beds. In the latter cases the ore is closer to the surface and the formations have a higher permeability. The author concludes that such temperature measurements may have some possibilities in prospecting for this type of ore deposit.

His determination of the rate of upward flow of heat represents a type of data needed for a better understanding of the structure of the earth's crust. The experimental technique is good and the conclusions drawn seem amply justified by the data. The material is well presented and the article is very easy to follow.

M. C. TERRY

Canadian Geophysical Bulletin of the National Research Council of Canada. Issued quarterly by the Associate Committee on Geodesy and Geophysics, *1* (October 1–December 31, 1947). 35 Pp.

A short review of the status of all the projects in applied and pure geophysics under way in Canada during the past year is presented in the fourth quarterly issue of this bulletin. In addition, a list of the members of the Associate Committee on Geodesy and Geophysics of the NRC of Canada, together with the dates of expiration of their office, is also included. The various names of members of the different committees comprising the many sections and major divisions of the National Committee for Canada of the International Union of Geodesy and Geophysics are also available in this issue.

There are too many individual projects to discuss them in detail although information regarding many of those of interest to geophysicists are available in reviews of this publication appearing in earlier issues of *Geophysics* for this year. However, the generalization may be made from an analysis of the individual reports that pure and applied geophysical research is being vigorously pursued in nearly all of its many branches by the Canadian geophysicists, and this bulletin constitutes a convenient way for keeping up with the details and progress of these various projects.

R. A. GEYER

1947 Summary of Nuclear Data compiled by the Nuclear Data Committee, Clinton National Laboratory. *Nucleonis*, Pt. 2 (May, 1948). Pp. 82–186.

This article, which appears as a separate portion of the May issue, constitutes a handy reference volume on data pertaining to nuclear reactions and related radioactive phenomena, including such factors as cross sections, masses, abundances and moments. All energies are given in Mev's unless otherwise stated and all cross sections in barns (10^{-24} cm^2). These tables of nuclear data are arranged according to the periodic table of elements and the information is presented in four columns with the headings "Atom or Molecule," "Information," "Remarks," and "Reference." The reference citation for each item of information does much to add to the value of this compendium. A two-page list of the journals surveyed for these nuclear data is also included together with several columns explaining the abbreviations used in the main section. These data should be of special interest to geophysicists engaged in the radioactive phases of geophysical research and prospecting.

R. A. GEYER

Japanese Geophysical Research. British Intelligence Objectives Subcommittee, Report No. B.I.O.S. J.A.P./P.R./758 (January, 1946). Pp. 1–23.

Japanese Research Institutions in the Field of Mining and Geology (A Preliminary Report). British Intelligence Objectives Subcommittee, Report No. B.I.O.S./J.A.P./P.R./852 (June 25, 1946). Pp. 9–124.

Technological Survey, Water Supply, Electrical Prospecting Equipment for Exploring Geological Formations and Natural Resources. British Intelligence Objectives Subcommittee, Report No. B.I.O.S./J.A.P./P.R./779 (March 20, 1946). Pp. 2–18.

The information in these three reports was compiled under the auspices of the British Intelligence Objectives Subcommittee and are readily available by writing to the British Information Service in Radio City, New York. The major portion of the first report discusses seismograph instruments used principally for earthquake detection. They are all mechanical types and very little immediate application could be found for their use in geophysical prospecting, although it is possible that one or two of the instruments, such as the Sassa strain seismograph and extension meter, might have some application in seismic research on such subjects as the magnitude of the horizontal displacements cased by seismic waves.

An interesting section is also included in which some of the leading Japanese seismologists discuss methods for forecasting earth disturbances. Dr. Nakamura for example, believes that the general

region of an earthquake can be predicted by statistical methods and that magnetic anomalies can be used to determine the intensity. He also believes that fluctuations in the natural earth currents occurring 24 hours prior to an earthquake are significant but are of too short notice to be practical.

The Tsuboi gravity pendulum described in some detail does not represent any radical changes in principle or design from known commercial types and the same applies to the Hasegawa gravity variometer.

The second report constitutes a handy reference volume for anyone interested in the specialties and qualifications of most of the leading geologists and geophysicists in Japan. In addition, a summary of wartime research in Japan in the field of mining and geology is included as well as a list of the research institutions in the field of mining and geology, together with a list of journals of the geological sciences published in Japan.

The third report represents the results of the interrogation of a number of specialists in geophysics, engineering and geology working in the fields of water supply. Most of the information involves a discussion of electrical methods and instruments used in Japan for the purposes mentioned in the title, but nothing new is reported.

R. A. GEYER

"Relationships Between Filtration Potentials and Permeability of Rocks," by V. N. Daknov. *Transactions of the Moscow Petroleum Institute*, No. 4 (1946).

It is not clear whether this paper purports to deal generally with the nature of the potential measured in electric well logging, or whether it is meant to treat solely that portion of the total potential which may be attributable to the streaming potential. The internal evidence indicates the former.

If it be assumed that Daknov intended to explain the total logging potential in terms of streaming potential, his paper is open to the criticism that electrokinetic effects account for only a minor portion of the total potential observed. It has been shown by Dickey[1] and by Mounce and Rust[2] that the shale is the dominant effect observed in the measurement of logging potentials, and further, by these and others, that the streaming potential ordinarily contributes only some 10 percent or so of the total.

Even if it be assumed that Daknov intentionally restricted his paper to a discussion of the contribution made by electrokinetic effects to the total logging potential, his work suffers from several serious omissions. For instance, he does not take into consideration the effect of the mud filter cake inevitably present in a borehole. This filter cake usually has a permeability several orders of magnitude less than that of permeable sands. It acts to reduce the flow of fluid through permeable zones, and thus tends to equalize the magnitude of the streaming potentials developed by the movement of fluid into porous zones of different permeabilities. Again, although Daknov calls attention to the second-order effects of porosity and immobile water within the pore spaces of sediments, he neglects to emphasize the first-order effects of resistivity of the fluid and of lowering of the zeta potential by the presence of electrolytes.

Although Daknov's analytical treatment of the relation of streaming potential to properties of the medium is ingenious, some of the auxiliary relations which he utilizes are of doubtful validity. That of the amount of immobilized water to porosity of the rock, for example, apparently is without physical basis.

All in all, Daknov's paper cannot be recommended as a source of information either for those seeking knowledge of logging potentials or for those interested in elecktrokinetic phenomena *per se*. The former can gain more from the work of Dickey, and of Mounce and Rust, and the latter will find more profitable the excellent papers of Bull and Gartner,[3] and of Neale.[4]

MILTON WILLIAMS

[1] P. A. Dickey, *Trans. AIME, 155* (1944), 39.
[2] W. D. Mounce and W. M. Rust, *Trans. AIME, 155* (1944), 49.
[3] H. B. Bull and R. A. Gartner, *Journal of Physical Chemistry 36* (1932), 111.
[4] S. M. Neale, *Trans. Faraday Soc. 42* (1946), 473.

PUBLICATIONS RECEIVED

Air Technical Intelligence-Technical Data Digest, Vol. 13, No. 12 (15 June 1948), Vol. 13, No. 13 (1 July 1948), Vol. 13, No. 14 (15 July 1948), Vol. 13, No. 15 (1 August 1948)

American Journal of Science, Vol. 246, No. 7 (July 1948)

American Petroleum Institute Quarterly (July 1948)

Prof. Arnaldo Belluigi, Faculty of Sciences, University of Cagliara, Italy.

"*La Misura Diretta Dei Campi Elettromagnetici Secondari Dei Suoli (il Mind)*" (1948)

"*La Geofisica Mineraria e la Sardegna*" (1945)

"*Curve Universali per il Calcolo di Influenze Elettromagnetiche (E.M.)*" (1946)

"*L'induzi one Elettromagnetica in un Suolo Omogeno Isotropo d'una Bobina Circolars in un Piano Verticale*" (1946)

"*Cartografie di campi Elettromagnetici Nei Suoli a Polarizzazione Ellitica e Loro Impiego*" (1947)

"*La Distribuzione, in Superficie, della Corrents Continua, nel Caso di uno Strato Conducente Inclinato*" (1947)

"*Skin-Effect e Correnti Vorticose nei Suoli Omogenei Interessati da Corrents Alternata*" (1946)

"*Fondamenti di una Nuova Prospezione Geolettrica*" (1947)

"*Il Problema dell'Induttore E. M. Orizzontale Circulare*" (1946)

Bohrtechniker-Zeitung, Jahrg. 64, Heft 3, Heft 4, Heft 5 (1948)

Bulletin of the Seismological Society of America, Vol. 38, No. 2 (April 1948)

Economic Geology, Vol. XLII, No. 4 (June–July 1948)

Geofisica Pura e Applicata, Vol. XII, Fasc. 1–2 (Maggio 1948), Fasc. 3–4 (Giugno 1948)

Institute of Petroleum Review, Vol. 2, No. 17 (May 1948), Vol. 2, No. 18 (June 1948)

Journal of Applied Physics, Vol. 19, No. 6 (June 1948), Vol. 19, No. 7 (July 1948)

Journal of the Institute of Petroleum, Vol. 34, No. 293 (May 1948), Vol. 34, No. 294 (June 1948)

Nafta Roc. IV, Nr. 5 (May 1948) Roc. IV, Nr. 6 (June 1948)

Proceedings of the Cambridge Philosophical Society, Vol. 44, Part 3 (July 1948)

The Review of Scientific Instruments, Vol. 19, No. 5 (May 1948), Vol. 19, No. 6 (June 1948), Vol. 19, No. 7 (July 1948)

Revista Geomineraria, Anno VIII, No. 2 (1947)

Transactions American Geophysical Union, Vol. 29, No. 3 (June 1948)

World Petroleum, (June-July-August 1948)

Zeitschrift für Erzbergbau und Metallhüttenwesen, Band I, Heft 1 (April 1948) Band I, Heft 2 (May 1948)

The publications listed above have been placed in the Exchange Depository of the Society at the University of Tulsa Library. They are available to Members of the Society, and may be borrowed upon request. Address all inquiries to the Business Manager, Box 1614, Tulsa 1, Oklahoma.

CONTRIBUTORS

A. A. BRANT was born in Toronto in 1910. He received the M.A. degree in mathematics and physics from the University of Toronto in 1933, and the Ph.D. degree in geophysics from Berlin University in 1936. He was the recipient of two gold medals and four scholarships during his university career, one of which was the Queen's Scholarship in physics at Princeton University in 1934. He was a member of the First Hockey Team of the University of Toronto and coached the German National Team in 1935 and 1936. He has held positions of Associate Professor of Geophysics at the University of Toronto and consultant to the Neument Mining Corporation and associates, Labrador Mining and Exploration, N. H. Temmins and Company, Northern Canada Mines, and others.

Dr. Brant is a member of the Society of Exploration Geophysicists, the American Institute of Mining and Metallurgical Engineers, The Canadian Institute of Mining and Metallurgy, the Society of Professional Engineers of Ontario, and other societies.

A. A. BRANT

D. M. DAVIDSON

D. M. DAVIDSON was educated at the University of Minnesota where he received the degree of Ph.D. in economic geology in 1928. Thereafter he was employed by A. Chester Beatty's company, Selection Trust, Ltd., of London, and spent the next five years as Chief Geologist largely in the exploration and development of the great copper fields of Northern Rhodesia. Until 1940, when the war interrupted his work, as Senior Engineer he examined and evaluated mining properties in many parts of the world. Since 1940, he has been Chief Geologist and Manager of Exploration for the E. J. Longyear Company, continuing the same type of work.

At intervals he has been visiting lecturer at some of the larger universities in the United States and abroad, and has written several articles on mining properties, with emphasis on the evaluation of mineral deposits.

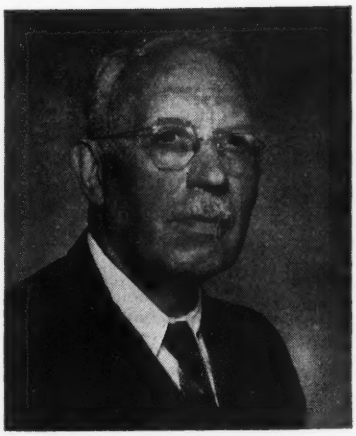
Dr. Davidson is a member of The Geological Society of America, the Society of Economic Geologists, the American Institute of Mining and Metallurgical Engineers, the Canadian Institute of Mining and Metallurgy, and the American Geophysical Union.

LEENDERT DE WITTE

LEENDERT DE WITTE was born in Bergen op Zoom, Holland, in 1925. He completed his undergraduate work in geology at the University of Groningen. He escaped occupied Holland via Spain in 1943 and served three years in the Netherlands East Indies Army. After being seriously wounded on Java, he was returned to Holland and upon his recovery, he came to the United States. In 1947 he received a M.S. degree in geophysics at the California Institute of Technology, after which he worked six months as a Schlumberger operator in Venezuela. He is now back at the California Institute of Technology working toward a Ph.D. in geophysics.

E. A. ECKHARDT was trained in physics at the University of Pennsylvania, receiving the degrees of B.S. in 1908 and Ph.D. in 1912. He spent the following year at the University of Goettingen, Germany, on a post-doctorate fellowship. He was on the staff at his alma mater from 1908 to 1917, and at the U. S. Bureau of Standards from 1917 to 1924. Late in 1924, he was employed by the Marland Oil Company to organize one of the first oil company geophyscial departments. Late in 1928, he accepted a similar appointment with the Gulf Oil Corporation. From 1929 to 1946, he was in charge of the Geophyiscal Division of the Gulf Research and Development Company, and since 1942, has been a Vice President of that organization.

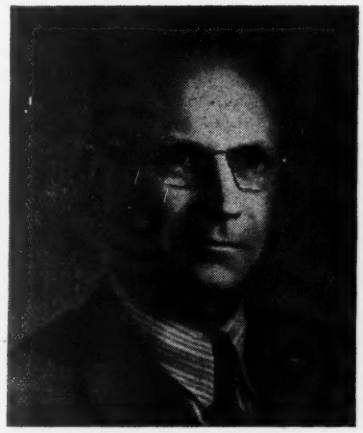
Dr. Eckhardt is a past president of the Society of Exploration Geophysicists, and is at present its representative as a director of the American Geological Institute. He is also a past president of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union, a member of the American Association of Petroleum Geologists, and numerous other scientific societies in the United States and abroad.



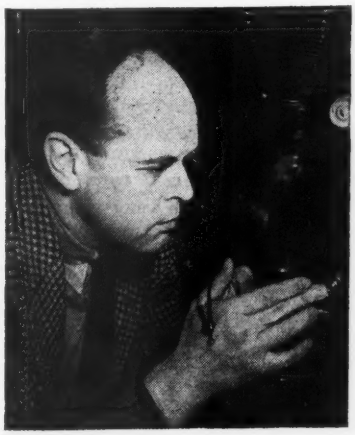
E. A. ECKHARDT

GEORGE M. SCHWARTZ was trained in the Universities of Wisconsin and Minnesota, receiving his Bachelor and Master's degrees from Wisconsin in 1915 and 1916, and his Ph.D. from Minnesota in 1923. He served as a Second Lieutenant in the U. S. Army in World War I.

During the field seasons of 1914, 1915 and 1919, he was employed as geologist for the Wisconsin Geological Survey, and from 1916 to 1917, was geologist for the Copper Range Company in Painedale, Michigan. From 1919 to date, he has held all ranks from instructor to professor, and Director of the Minnesota Geological Survey at the University of Minnesota. From 1940 to 1941, he was visiting professor at Laval University, Quebec; has been field and consulting geologist in Minnesota, Michigan, Montana, Wyoming, Colorado, and Arizona; from 1944 to 1947, he was senior geologist on part time for the U. S. Geological Survey; and during the present summer, is engaged in professional work in the Bisbee district. His principal field of research is economic geology and petrology.



GEORGE M. SCHWARTZ



HARRY WARREN

HARRY V. WARREN received from the University of British Columbia the degrees of B.A. in 1926 and B.A.Sc. in 1927. From 1926 to 1929, he was a Rhodes Scholar at Oxford University, receiving the degrees of B.Sc. in 1928 and Ph.D. in 1929. From 1929 to 1932, he was a Commonweatlh Fund Fellow at the California Institute of Technology, and since that time he has taught mineralogy and petrology at the University of British Columbia.

Photographs and biographies of contributors to this issue not appearing above have been published previously, as follows: H. M. Evjen, Vol. VIII, No. 2 (April 1943). C. A. Heiland, Vol. VII, No. 1 (January 1942). Wm. Bradley Lewis, Vol. X, No. 1 (January 1945).

SOCIETY ROUND TABLE

NOMINEES FOR 1949–50 EXECUTIVE COMMITTEE

The following brief biographical sketches are presented to acquaint members of the Society with nominees appearing on the official ballot which will be mailed to all voting members at a later date.

FOR PRESIDENT

ANDREW GILMOUR

M. M. SLOTNICK

ANDREW GILMOUR received his B.Sc. degree from Queen's University, Belfast, Ireland in 1918 and his M.Sc. from the National University of Ireland in 1919. In 1920 and 1921 he was engaged in research work for the British Admiralty at the Admiralty Laboratories, Teddington, Middlesex, England.

In 1922 he came to Amerada Petroleum Corporation to do Torsion Balance work and has been with Amerada and its affiliated companies continuously since that time. From 1928 to 1930 he supervised geophysical work for Amerada in California. Since 1930 he has been supervising geophysical work, mainly seismograph work, in the Mid-continent. He is now Chief Geophysical Supervisor for Amerada Petroleum Corporation.

He is a member of the Society of Exploration Geophysicists (Secretary-Treasurer 1940–1941, Vice President 1948–1949), American Association of Petroleum Geologists, American Geophysical Union, American Association for the Advancement of Science, The Tulsa Geological Society, and the Geophysical Society of Tulsa.

MORRIS MILLER SLOTNICK was graduated from Harvard University with an S.B. degree in 1922 and subsequently received an M.A. (1925) and a Ph.D. (1926) in mathematics from the same University. He spent the next year as a Travelling Fellow in Hamburg, Germany and was a National Research Fellow at Princeton (1927–1928). After some time as Instructor at Harvard, he jcined the Humble Oil and Refining Company in 1930.

Until 1936 he served as research mathematician in the Geophysical Research Department and since then he has been Supervisor of Geophysical Interpretation in the Exploration Department.

During World War II, he was on leave of absence to work in the Naval Ordnance Laboratory and Bureau of Ordnance, Navy Department in charge of a section in analysis.

In the Society of Exploration Geophysicists, he occupied the post of Editor for the years 1937 and 1938.

FOR VICE-PRESIDENT

ROY L. LAY

GEORGE E. WAGONER

ROY L. LAY received his B.S. degree in Electrical Engineering from Rice Institute in 1928. Upon graduation from Rice he was employed by the Geophysical Research Corporation as an Observer and was later promoted to Computer and Party Chief.

Mr. Lay was employed by The Texas Company as Party Chief in April, 1932 and during the next several years initiated this company's reflection work in Texas, Louisiana, California and the Rocky Mountain area. He was promoted to Field Supervisor in 1937, and during the next year made a supervisory trip to Colombia and Venezuela, South America, and was in charge of the seismic, gravity and magnetometer work in Egypt. In July, 1943 he was promoted to Assistant Chief of the Geophysical Division and in September, 1945 was advanced to Assistant Manager, which position he currently holds.

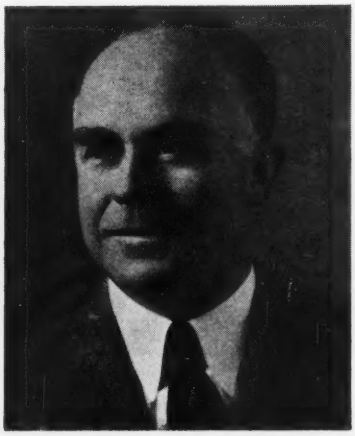
He is a member of the American Association of Petroleum Geologists, the Houston Geological Society, and the Society of Exploration Geophysicists, both the local and national organizations. He was Second Vice-President of the S. E. G., Houston Section in 1947–1948 and was recently elected President of the Houston Section for the 1948–1949 term.

GEORGE E. WAGONER received a degree of Geological Engineer from the Colorado School of Mines in 1928. He was employed as a Geologist and Geophysicist by John H. Wilson, Consulting Geologist and Geophysicist of Golden, Colorado, from June 1928 to May 1930. He was employed by Humble Oil and Refining Company from 1930 to 1934 as a Torsion Balance Observer, Seismograph Computer, and Seismograph Party Chief. In 1934, he was loaned to The Carter Oil Company as an assistant to the Chief Geophysicist. In 1935, he was transferred to The Carter Oil Company as Supervisor of Geophysical Operations. In 1936, he was transferred to the Standard Oil Company of Louisiana as Chief Geophysicist. In 1937, he returned to The Carter Oil Company as Assistant Chief Geophysicist in charge of Geophysical Exploration. In August 1946 he was appointed Manager of

Exploration for the Southern Division of The Carter Oil Company, Shreveport, Louisiana. He is a member of the Society of Exploration Geophysicists being Secretary-Treasurer, 1945–46, Chairman of the Public Relation and Publicity Committee 1947–48, member of the Constitutional Committee 1947–48, Chairman of the Shreveport regional Committee 1947–48, Chairman of the Public Relations and Publicity Committee 1948–49. Member of the Ark-La-Tex Geophysical Society, President 1947–48 and member of the executive committee 1948–49. Member of the American Association of Petroleum Geologists and the Shreveport Geological Society.

FOR SECRETARY-TREASURER

KENNETH E. BURG



CURTIS H. JOHNSON

KENNETH E. BURG received his B.S. degree in Electrical Engineering from the University of Texas in 1926. Upon graduation he was employed by The Geophysical Research Corporation to do experimental geophysical work. Mr. Burg was computer and observer on one of the original experimental reflection crews and was in charge of several electrical prospecting crews prior to the time he was made Party Chief on a large refraction crew in 1928.

In 1930 he resigned to join the newly-formed Geophysical Service Inc. As Party Chief with that organization, he worked in the Gulf Coast, Mid-Continent, and Pacific Coast areas, and in Canada. He was placed in charge of the Southern Louisiana and Mississippi areas as District Supervisor in 1936, where he was instrumental in developing the techniques and equipment used in that area. In 1941 he was placed in charge of the Research Department in the Dallas Laboratories of Geophysical Service Inc.

Mr. Burg resigned in 1942 to join the Stanolind Oil and Gas Company as Seismograph Technician. In 1943 he was made head of the Seismograph Department, and in 1944 promoted to Geophysical Supervisor in charge of all the geophysical operations of the Stanolind Oil and Gas Company. He rejoined Geophysical Service Inc. in January, 1947, as Consulting Geophysicist, which position he now holds.

Mr. Burg is a member of the Society of Exploration Geophysicists, American Association of Petroleum Geologists, American Geophysical Union, Seismological Society of America, The Dallas Geophysical Society, Institute of Radio Engineers, and Tau Beta Pi Honorary fraternity. He has served on the Research Committee of the American Association of Petroleum Geologists, and has served the S.E.G as a member of the regional program committee, and in preparation of the recently

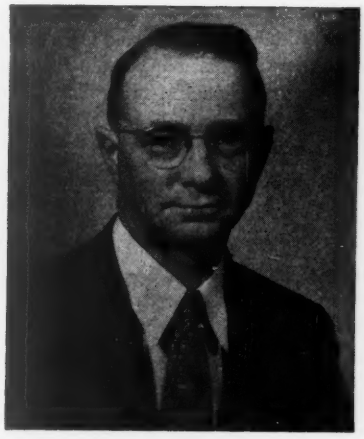
published Cumulative Index. At present he is Vice-President of the Dallas Section and is Chairman of the Dallas Regional Program Committee.

CURTIS H. JOHNSON was graduated from the University of California at Los Angeles in 1932 with an A.B. and Honors in Physics, and took postgraduate work in acoustics, also at U.C.L.A. From 1933 to 1938, he was Geophysicist and later Chief Geophysicist with Rieber Laboratory. From 1939 to the present date, he has been Geophysicist with the General Petroleum Corporation.

Mr. Johnson is a member of the Society of Exploration Geophysicists, the American Association of Petroleum Geologists and the American Geophysical Union. He has served the S.E.G. as Vice-Chairman of the Arrangements Committee for the National Convention in Los Angeles in 1947, and as chairman of the Pacific Coast Program Committee for the 1948 National Convention and the 1947 Pacific Coast Regional Meeting. He is currently completing a term as President of the Pacific Coast Section of the Society of Exploration Geophysicists.

FOR EDITOR

RICHARD A. GEYER



SIGMUND HAMMER

RICHARD A. GEYER received his B.S. and M.S. degrees from New York University in 1937 and 1940 respectively. In addition to doing graduate work at Fordham and Columbia Universities in seismology and general geophysics, he also instructed in geology at Princeton University from 1939 to 1942. He was engaged at various times between 1938 and 1942 by Standard Oil Company of New Jersey on several geophysical and geological research projects.

He was in charge of a degaussing range for the U. S. Navy during the early part of the war and subsequently did research and instructed in underwater sound and oceanography on a Navy program conducted by the Woods Hole Oceanographic Institution at Woods Hole, Massachusetts. Since 1945 he has been employed by the Humble Oil and Refining Company as a Research Geophysicist.

Mr. Geyer has served for several years on the Special Reviews Committee of *Geophysics* and in the capacity of Chairman of that Committee since 1947, as well as a member of the abstracting staff of the Annotated Bibliography of Economic Geology from 1938 through 1940. He is also a member of the American Geophysical Union, the Institute of Radio Engineers, and the American Association of Petroleum Geologists.

SIGMUND HAMMER was born August 13, 1901, in Webster, South Dakota, where his father was for many years a Norwegian-Lutheran Minister. He received the B.A. Degree at St. Olaf College, Northfield, Minnesota, in 1924. As a student assistant in the Physics Department there he participated in the design, construction, and operation of the college broadcasting station, WCAL, which is still in operation. From 1924 until 1929 he was teaching fellow and graduate student in the Physics Department at the University of Minnesota where he received the Ph.D. Degree (Major: Physics; Minor: Mathematics). During this period, summers were spent in employment as radio operator on board ship, research assistant and Radium Technician in the University Hospital.

Dr. Hammer has been employed in the Gravity Interpretation Section of the Geophysics Division of the Gulf Research & Development Company, Pittsburgh, Pennsylvania, since 1929, and has had charge of the section since 1946. He also is a Lecturer in Geology at the University of Pittsburgh, where he teaches a course in Geophysical Prospecting. He has published several technical papers on the gravitational field of the earth, Geophysical Prospecting, and Geophysical Applications of the Statistical Theory of Errors.

Dr. Hammer is a member of the American Physical Society, Physical Society of Pittsburgh (Secretary-Treasurer 1941, Vice President 1942, President 1943), American Association for the Advancement of Science, New York Academy of Science, Pennsylvania Academy of Science, Sigma Xi, American Association of Petroleum Geologists, American Geophysical Union (member, Special Committee on the Geophysical and Geological Study of the Continents), and the Society of Exploration Geophysicists (Chairman, Regional Program Committee for the Eastern States; General Chairman for Eastern Regional Meeting in Pittsburgh in 1947).

STANDING COMMITTEES FOR THE YEAR 1948–1949

In order to conserve space, the names, companies and addresses of committee chairmen only are given below.

Nominations

L. L. Nettleton, Gravity Meter Exploration Company, 1348 Esperson Bldg., Houston 2, Texas.

Program and Arrangements

(Annual Meeting)

Andrew Gilmour (General Chairman), Amerada Petroleum Corp., Box 2040, Tulsa 1, Oklahoma.

Regional Program and Arrangements Committees

Dallas: K. E. Burg, Geophysical Service Inc., 6000 Lemmon Ave., Dallas 9, Texas.
Eastern Region: Sigmund Hammer, Gulf Research and Development Co., Drawer 2038, Pittsburgh 30, Pennsylvania.
Fort Worth: A. A. Hunzicker, The Texas Co., Box 1720, Ft. Worth, Texas.
Houston: J. C. Pollard, Robert H. Ray Company, 1914 National Standard Bldg., Houston 2, Texas.
Pacific Coast: Maynard W. Harding, United Geophysical Co., 595 E. Colorado St., Pasadena 1, California.
Shreveport: L. F. Fischer, Sohio Petroleum Co., Box 1667, Shreveport, Louisiana.
Tulsa: Francis F. Campbell, Amerada Petroleum Corp., Box 2040, Tulsa 1, Oklahoma.

Education

Rev. J. B. Macelwane, S.J., Institute of Technology, St. Louis University, 3621 Olive St., St. Louis 8, Missouri.

Student Membership

V. L. Jones, 1412 South Norfolk, Tulsa, Oklahoma, Consulting Geophysicist and Ass't. Prof. of Geophysics, The University of Tulsa.

Chairmen of Other Committees

Annual Survey of Geophysical Activity

E. A. Eckhardt, Gulf Research and Development Co., Drawer 2038, Pittsburgh 30, Pennsylvania.

Geophysical Case Histories, Volume I

Henry C. Cortes, Magnolia Petroleum Co., Box 900, Dallas 1, Texas.

Public Relations and Publicity

George E. Wagoner (General Chairman), The Carter Oil Company, Drawer 1739, Shreveport, Louisiana.

Radio Frequency Allocation

R. D. Wyckoff, Gulf Research and Development Co., Drawer 2038, Pittsburgh 30, Pennsylvania.

Special Reviews

R. A. Geyer, Humble Oil and Refining Co., Box 2180, Houston 1, Texas.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the President within thirty days. (Names of references appear in parentheses after the name of each nominee.)

ACTIVE

Addison LaFayette Barnes (W. J. Osterhoudt, J. E. McGee, W. B. Lee)
Jackson Mounce Barton (T. J. Bevan, T. D. Mayes, H. C. Cortes)
Ronald Eugene Beck (W. H. Courtier, A. J. Hintze, J. R. Johnson)
Gordon Rutledge Bell (D. Walling, E. H. Vallat, E. L. Erickson)
William H. Berleth (W. M. Rust, Jr., W. D. Mounce, M. C. Terry)
Idris Christopher Joseph Bourne (E. J. P. van der Linden, W. Frost, C. C. Fitch)
Burton Hill Boyum (W. A. Longacre, E. I. Derby, Jr., L. Bacon)
Joseph Brightwell Alexander (C. H. Dix, G. W. Potapenko, B. Gutenberg)
Richard Lawrence Congdon (E. J. Stulken, P. E. Haggerty, K. E. Burg)
Ralph Johnson Copeland (W. J. Osterhoudt, J. E. McGee, W. B. Lee)
Robert Marx Dreyer (J. J. Jakosky, C. H. Wilson, R. R. Petson)
Christopher Paul Durant (G. D. Gibson, R. Bradley, R. H. Tucker)
Kirby Emerson Etheridge (R. H. Ray, J. B. Nichols, P. T. Rumsey)
Raymond John St. Germain (D. F. Brounard, G. H. Harrington, C. C. Hutchinson)
George Randall Gibson (T. P. Ellsworth, S. Harris, D. Walling)
Harry George Hadler (R. C. Coffin, G. V. Dunn, R. A. Weingartner)
D. B. Harris (A. J. Barthelmes, J. G. Jackson, C. E. McClure)
John Robert Hayes (J. G. Patrick, D. P. Carlton, W. W. Longley)
James Berry Hazelrigg (W. H. Taylor, W. Lee Moore, W. L. Crawford)
William Otto Heap (A. J. Barthelmes, H. M. Thralls, T. A. Manhart)
John Henry Hidy (J. A. Sharpe, A. F. Cline, J. C. Rollins)
Taylor Hugh Holland (D. H. Gardner, J. W. Bolinger, G. F. McReynolds)
William Holt McGuire (H. C. Moore, J. P. Garner, K. A. Robertson)
Sidney Kaufman (F. A. Van Melle, K. R. Weatherburn, N. D. Smith, Jr.)
Jasper Ridgely Leggett (E. V. McCollum, C. Ferris, R. C. Holmer)
Finis Mack Samford (H. G. Patrick, M. M. Slotnick, J. A. Brooks)
Patrick Bernard McGrath (R. G. Sohlberg, F. A. Hale, J. A. Long)

Joseph Rufus McMahan, Jr. (G. E. Bader, A. G. Starr, R. S. Duty)
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Paul Wagner Netterstrom (W. H. Fenwick, W. L. Hershelman, J. Spencer)
John Wallace Newquist (G. S. Lambert, H. L. Thomsen, H. L. Schiflett)
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Hanford Paul White (W. L. Homan, P. J. Rudolph, J. B. Barbisch)
Charles Edwin Riddell (M. W. Harding, C. H. Gerdes, E. G. Schempf)
Richard Duff Roberts (R. F. Bennett, B. Stewart, D. Crary)
Artemio Maureira Rodriguez (L. K. Morris, B. F. Grossling, M. W. Harding)
Lewis Brann Rogers (M. M. Slotnick, R. S. Duty, Jr., H. G. Patrick)
James Watson Rupert, Jr. (L. J. Peters, R. B. Ross, W. C. Lamb)
Frederick Albert Smith (R. F. Bennett, S. B. Stewart, W. W. Butler)
Herbert Bell Smyrl (W. L. Homan, T. L. Allen, W. L. Moore)
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Kermitt C. Thompson (W. A. Matthews, S. Harris, Karl Dyk)
Eugene James Toomey (C. H. Green, P. E. Haggerty, E. McDermott)
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Frank Ritchie Wallace (H. C. Cortes, G. D. Mitchell, Jr., R. K. Carter)
Richard Hauser Wardell (C. J. Donnally, D. Walling, H. D. Marshall)
William Edmond Ware (R. R. Phillips, J. H. Todd, S. W. Totten)
Frank Barnard Wigbell (W. J. Osterhoudt, W. B. Lee, J. E. McGee)

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Joseph Howard Gautreaux (B. D. Farrow, J. E. Jett, W. W. Newton)
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William Glass Hazen (L. J. Peters, S. Hammer, William C. Lamb)
Stanley Allen Hatcher (R. F. Bennett, D. Crary, S. P. Stewart)
Richard Alan Herrod, Jr. (E. W. Frowe, R. H. Ray, J. C. Pollard)

Delmar Ellis Hill (C. H. Green, R. C. Dunlap, E. A. Kiesler)
Paul Van Hodge (E. Thomas, D. Coursey, H. B. Peacock)
John Duke Horton (J. E. Stones, C. E. Reel, F. Ittner)
Rodney Wayne Jackson (P. L. Lyons, D. E. Ward, M. Romberg)
Melvin Coatany Johnson (B. Farrow, H. Brown, J. A. Waller)
James Brown Jordan (C. J. Donnally, D. Walling, V. E. Prestine)
James Douglas Keese (W. H. Smith, G. A. Schofield, R. L. Lay)
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Robert Thompson Keys, Jr. (B. C. Tucker, S. W. Fruehling, R. E. Lee)
James Seymour Latenser (C. Green, R. Dunlap, E. Kiesler)
Paul Roland LeTourneau (R. F. Beers, B. D. Farrow, G. E. Seiler)
Robert Irving Levorsen (H. H. Hickey, J. Todd, E. T. Nichols)
James Walker Locke (H. R. Thornburgh, F. H. Agee, B. Sorge)
Maurice Mainguy (E. G. Leonardon, E. Boissonnas, J. C. Legrand)
Robert Holden Peacock (F. Ittner, C. E. Reel, T. E. Dennis)
Warren N. Pearce (K. A. Robertson, B. W. Sorge, J. C. Hoffman)
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Joseph Stanley Pluta (E. J. Smith, Jr., R. E. Davis, C. J. Hardy)
Dwayne Lewis Pretzer (E. D. Gaby, J. H. Todd, G. Augustat)
John Edward Procter (C. A. Chapman, F. A. Roberts)
Richard Stanley Rector (J. Everitt, R. C. Dunlap Jr., E. A. Kiesler)
Victor William Smith (C. J. Donnally, D. Walling, V. E. Prestine)
Thomas James Reid, Jr. (E. van der Linden, A. A. Fitch)
Gerald Alfred Reingans (E. Thomas, H. B. Peacock, D. Coursey)
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Thomas Edward Robinson (J. E. Jett, D. W. Autrey, B. D. Farrow)
Antonio Maria Selem (E. J. P. van der Linden, A. A. Fitch, A. J. Barthelmes)
Cecil Fay Shelton (G. H. Westby, J. E. Dorris, S. W. Schoellhorn)
Leon van der Harst (E. van der Linden, A. A. Fitch, H. H. Brons)
Richard Andrew Voigel (R. W. Mossman, E. H. Kurk, H. H. Andrews)
Heinz Broer Vos (E. van der Linden, A. A. Fitch, E. B. Lindsey)
Lucius Wesley Waterman (R. A. Dunlap, E. Kiesler, C. Green)
Charles Andrew Weeth (A. G. Starr, J. A. Brooks, Jr., R. S. Duty, Jr.)
William Joseph Whaley, Jr. (H. G. Patrick, R. S. Duty, Jr., A. G. Starr)
Dexter Earl Williams (W. L. Moore)
Oliver Barker Winstanley (E. van der Linden, A. A. Fitch, H. H. Brons)
Richard Franklin Zimmerly (E. R. Locke, R. Holmer, H. Stommel)

STUDENT

Edward Irving Barton (E. L. Miller, Jr.)
Samuel Bohrer (M. H. Gilmore, V. J. Blum, F. Robertson)
Edwin Henry Bruenger (J. B. Macelwane, V. J. Blum, F. Robertson)
Cecil Carter Miller, (J. B. Macelwane, V. J. Blum, F. Robertson)
Arthur Stanley Dickinson (B. H. Parker, R. Holmer, W. Mason)
Salahi Diker (R. C. Holmer, G. T. Meredeth, G. Poole)
Anthony Mario Di Renzo (R. C. Holmer)
William Robert Drake (J. T. Wilson)
James Richard Engelhardt (J. B. Macelwane, V. J. Blum, F. Robertson)
Hugh Evans, Jr. (R. C. Holmer, F. M. VanTuyl, J. H. Johnson)
Thomas Robert Eugene Goedicke (T. Koulomzine, J. L. Miller, Jr., J. L. Stuckey)
Robert Stroud Houston (E. L. Miller, Jr.)
Robert Hiteshew Insley (W. W. Longley)

Vance Clifford Kennedy (L. O. Bacon)
Philip Linwood Lawrence (R. C. Holmer, H. E. Stommel, W. S. Levings)
Darragh Hawthorne McFadden, Jr. (R. Holmer)
Harold Meadow (J. T. Wilson)
Otto William Nuttli (J. B. Macelwane, V. J. Blum, F. Robertson)
Dale Deming Ozman (W. W. Longley, L. A. Warner, M. O. Griffitts)
William Hill Powell, Jr. (E. L. Miller, Jr.)
Darrell Eugene Smith (H. V. W. Donohoo)
William Edgar Spradley (R. F. Bennett, S. B. Stewart, W. W. Butler)
David Johnson Stuart (L. O. Bacon)
William Hillard Throop (R. C. Holmer, W. S. Levings, G. T. Merideth)
Leonard A. Woker (J. B. Macelwane, V. J. Blum, F. Robertson)

TRANSFER TO ACTIVE MEMBERSHIP

Guy O. Buckner, Jr. Abdul Khaliq Mehta William Jarrott Harkey

TRANSFER TO ASSOCIATE MEMBERSHIP

William Allen, Jr. Henry H. Nogami

REINSTATEMENT

Raymond Thomas Cloud Robert Davenport
Frank Oliver Mortlock Charles E. Myers
Alfred Schleusener

RESIGNATION

Samuel Stewart West

ANNOUNCEMENT OF DALLAS REGIONAL MEETING

A Joint Regional Exploration Meeting of the S.E.G. and A.A.P.G. sponsored by the Dallas Geophysical Society, a local section of S.E.G., and the Dallas Geological Society will be held in November 18–19, 1948, in Dallas, Texas.

The Adolphus Hotel will be headquarters for the meeting; 100 double rooms will be available. Members desiring to attend are urged to make reservations directly through the hotel as far in advance as possible. When requesting reservations members should state that they plan to attend the Regional Meeting and should also give their preference as to rooming arrangements. Because of the limited number of single rooms available, you will stand a much better chance of securing accommodations if your request calls for rooms to be occupied by two or more persons.

A reception and dinner dance will be held at the Adolphus Hotel, Friday Evening, November 19th.

The following committees are in charge of the Meeting:

General Co-Chairmen

W. W. Newton
R. A. Stehr

Geological Society *Geophysical Society*

Program Committee

John M. Clayton, Temporary Chairman — K. E. Burg, Chairman
W. J. Wilseweck — E. D. Alcock
R. E. Rettger — D. H. Clewell
Edward Cram — W. B. Hogg
W. B. Moore — M. P. Jones

Housing & Entertainment Committee

John W. Clark, Chairman Chairman
Charles B. Carpenter
R. I. Searle.
D. Ray Dobyns
A. E. McKay

Finance and Publicity Committee

(Also in Charge of Registrations)

H. V. Tygrett
Marshall Fagin
W. G. Smiley, Chairman
J. H. Pernell
M. M. Garrett

DALLAS, TEXAS
OCTOBER 15, 1948

W. G. Smiley, Chairman
Finance and Publicity Committee

ANNUAL SPRING MEETING, PACIFIC COAST SECTION, BAKERSFIELD, CALIFORNIA JUNE 18, 1948

The Annual Spring Meeting of the Pacific Coast Section of the Society of Exploration Geophysicists was held during the afternoon and evening of June 18, 1948 in the Spanish Room of the Hotel El Tejon in Bakersfield, California. The meeting was under the direction of Loring B. Snedden, Vice-President of the Northern District. Approximately 70 persons attended the afternoon technical meeting; 80 persons were present for dinner; and some 95 persons were present for the evening paper and discussion.

AFTERNOON MEETING—2:00 P.M. TO 4:30 P.M.

The subject for the afternoon meeting was a symposium on "Location of Faults by Geophysical Methods." Two lead papers and four short contributions were presented. Discussion from the floor followed each paper, and a general discussion was held at the conclusion of the last paper.

Mr. Snedden was Chairman of the afternoon meeting.

Lead Papers:

"Fault, Their Character, Classification, and Importance" was presented by Mason Hill of Richfield Oil Company. Mr. Hill is a recognized authority on the subject of faulting, and his remarks from the point of view of the geologist were instructive as well as interesting to the geophysicists. Models were used to illustrate the classification of faults. The classification outlined by Mr. Hill lays stress on evidence the geologist may observe in the field, rather than on theoretical concepts.

"Fault Interpretation in Southwest Texas" was presented by Miller Quarles, Jr. of United Geophysical Company. Mr. Quarles presented a number of cross sections illustrating the nature of faulting in Southwest Texas. Sample seismograms were presented to show the high quality data on which the fault interpretations were based. Mr. Quarles pointed out reflection times near the fault plane on the up-thrown block of a normal fault often show an appreciable lag in travel time. A theory involving refraction along the fault plane was presented as an explanation of this observation.

Short Contributions:

"An Example of Fault Detection by Reflection Seismograph Methods" was presented by Dean Walling of Western Geophysical Company. Mr. Walling presented a cross section showing seismograph data of high quality. Two steep angle faults were indicated by correlation of the seismograms, as well as by definite breaks in the continuity of the section. Well control is present to further substantiate the observed facts.

"Seismic Cross Sections Across Faults Demonstrated by Well Control" was presented by O. F. Van Beveren of Standard Oil Company of California. Two seismic cross sections were shown and in each case well control established the presence of major faulting. It was noted that without well control, it would be difficult to detect the presence of faulting.

"Fault Example on West Side of the San Joaquin Valley, California" was presented by R. C. Dunlap, Jr. and E. A. Kiesler of Geophysical Service Inc. A seismic cross section plotted in time space was shown. A deep seated, high angle fault was indicated by correlation of the seismograms as well as by the abrupt termination of horizons at the postulated fault.

"An Earthquake Recorded by Reflection Seismograph Instruments" was presented by N. J. Lea of the Texas Company. The Observer in the field felt the earthquake, took a long record, and noted the time of day the quake was felt. A long train of high energy events is apparent on the seismogram. Notations as to the time of day enabled Mr. Lea to correlate the earthquake with observations made at several seismological stations in California.

The meeting was informal in nature, and a considerable amount of discussion was carried on throughout the afternoon. During the discussion period Loring Snedden displayed seismograms showing definite faulting in the Basement.

EVENING MEETING—7:00 P.M. TO 10:00 P.M.

Mr. Curtis H. Johnson, President of the Society, was Chairman of the evening meeting.

"Exploratory and Economic Aspects of Oil Development in Alaska" was presented by Herbert Hoover, Jr. of United Geophysical Company. Mr. Hoover also is a partner in the firm of Hoover, Curtis, and Ruby which, as one of the companies comprising Arctic Contractors, supervises the exploration phase of the operations in Naval Petroleum Reserve No. 4. A wide variety of topics were covered in a very informative and interesting manner. Among the topics receiving rather detailed treatment were geography, climate, personnel, transportation, and arctic techniques developed for seismic and gravity exploration. The interest in Mr. Hoover's subject was illustrated by the considerable amount of discussion that followed the paper.

Expression by members of the Society indicate a general feeling that Loring Snedden in this, the first technical meeting of the Pacific Coast Section of the Society of Exploration Geophysicsts, has set a high standard for future meetings of the Society.

R. C. DUNLAP, JR.
Secretary-Treasurer

HOUSTON SECTION ELECTS OFFICERS

HOUSTON SECTION OFFICERS: *Left to right,* J. C. POLLARD, R. L. LAY, W. J. OSTERHOUDT, E. W. JOHNSON, R. F. BENNETT, H. E. BANTA

The Society of Exploration Geophysicists-Houston Section held its final meeting of the first term on May 28, 1948, at The College Inn in Houston. Henry C. Cortes of Dallas and Paul Weaver, President of A.A.P.G., were guests who helped make the party highly enjoyable.

Following the dinner, the newly elected officers were introduced and installed in office. In mock ceremony each retiring officer presented to his successor his symbols and equipment of office. The new Treasurer received a shell game, to guess where the funds to run the society will come from; the new

Secretary was given a stock of worn-out pencils, and a supply of fine stationery rolled in its usual form. The second Vice President who is the entertainment chairman received a set of comic books, broken phonograph records, etc.; the new first Vice President, who is program chairman, received a comprehensive list of all people in the area who might be called to write papers for S.E.G.—the Houston telephone directory. The new President was presented with a bottle of S.E.G. soft soap, the president's needle, chisel and an eight pound steel maul for a gavel. Of course, each new officer received generous advice.

The officers for the Houston Section for the term June 1948 to June 1949 are: President: Roy L. Lay, The Texas Company; First Vice President: Jack C. Pollard, Robert H. Ray Company; Second Vice President: Earle W. Johnson, General Geophysical Co.; Secretary: Roy F. Bennett, Sohio Petroleum Corporation; Treasurer: H. E. Banta, Independent Exploration Co.

As proof of the interest in the Houston Section and its candidates for office, eighty percent of the active members who were qualified to vote mailed in their ballots. The Houston Section has enjoyed a good start; it will continue to grow and to encourage good fellowship and cooperation in geophysics.

W. J. OSTERHOUDT
Past President

DEADLINE FOR ACCEPTANCE OF PAPERS FOR THE 1949 ANNUAL MEETING

To allow time for programming papers for the 1949 Annual Meeting, the Program Committee has set January 1, 1949 as the deadline date for the submission of papers to be read at the meeting. Authors having papers planned for the 1949 meeting are urged to submit manuscripts with abstracts on or before the date.

FCC HEARING ON APPLICATIONS FOR RADIOLOCATION LICENSES

On July 19th and 20th the Federal Communications Commission conducted a hearing in Washington, D. C. on the applications of Seismograph Service Corporation and Frost Geophysical Corporation (Docket 8989) on both of which requests had been made for allocation of frequencies for the purpose of Class II experimental licenses to be used in connection with radio surveying methods for geophysical purposes.

The Society of Exploration Geophysicists and the American Petroleum Institute were represented at the hearing by Mr. R. D. Wyckoff, chairman of the S.E.G. Radio Facilities Committee and a member of the Central Committee on Radio Facilities of the API. In addition, certain oil company, geophysical and electronic research experts testified. The applicants furnished detailed descriptions of their respective radio surveying methods and general information on the geology of the Gulf Coast, the operational problems involved and the usefulness of radio surveying in the solution of the geophysical problems in this area. The points of major import which were stressed by the oil company witnesses, Mr. Don Carroll, Special Assistant to the Director of the Oil and Gas Division of the Department of Interior and by the applicants, were the urgent need of discovery of additional oil reserves for the benefit of the national economy and security; the importance of the Gulf tidelands areas as a potentially prolific source of additional oil and gas reserves; the need for improved radio surveying facilities to obtain greater range and accuracy in the conduct of the geophysical exploration of this area; and the usefulness of phase-measuring systems for this purpose.

Pertinent parts of Mr. Wyckoff's testimony are as follows:

"The expansion of geophysical exploration into offshore waters, and, indeed, into vast shallow ocean areas, such as the Bahamas, has forced the industry into the use of radio survey facilities as the only possible means for accomplishing such work. Similarly, the development of new techniques, such as the airborne magnetometer, has required the use of radio-location facilities for adequate flight control and mapping. Moreover, in mapping uncharted areas, radio surveying has proved invaluable, and on occasion the only practical method of obtaining geophysical control of aerial photography.

"The methods currently in use are radar, Shoran and phase-comparison, and the latter is in the experimental development stage only. . . .

"While the Shoran method has probably proved to be the most useful of the radio-survey methods available to the industry to date, the method definitely fails to fulfill the over-all requirements of geophysical operations because of its line-of-sight limitations. In offshore marine work, for example, the limited size of the mobile craft precludes the use of antenna much higher than fifty feet. With a similar height at the fixed transponder stations, the reliable range of the system does not exceed about 18 miles, and even with a 100-foot antenna at the fixed station, the reliable range is increased to only about 30 miles. This imposes a very serious limitation where large areas are involved and particularly if the system is to serve simultaneously more than one geophysical crew in the area. Thus, there is an urgent need to provide radio-surveying facilities free from the line-of-sight limitation."

In summary, Mr Wyckoff said, "It is the consensus of the industry, and I think we successfully obtained a very excellent cross-section of the industry on those questions, that facilities, that is, frequency allocation, should be available for continued use of radar, for continued use of Shoran and for the development of phase-comparison methods, low-frequency methods which eliminate our line-of-sight problem, now a big problem in radio surveying."

MEMORIAL

FRANK RIEBER, 1891–1948

FRANK RIEBER

Frank Rieber, one of the most colorful and widely known of the pioneers in geophysics, died on June 30, 1948, in New York City. His death followed ten years of a serious heart affliction which caused no apparent decrease in his energy and enthusiasm for his work. His death thus came as a decided shock to many of his friends in the geophysical field.

He was not one of the big operators in geophysical contracting, nor were all the results of his research widely accepted. Nevertheless his activities in the field of geophysics served as an example and a goad to the industry to prevent complacency and stagnation. He was, of course, not the only such example, but was probably the best known and the most discussed rebel in the geophysical ranks.

To understand Frank Rieber one must understand his guiding principles. He was a supreme egotist and supremely self confident. Hardly a detail of his designs and never a complete design followed accepted practices or utilized accepted methods. To him there was always a better way of doing that which had been done before, and that which was considered impossible or impracticable was to him simply a challenge he could not ignore. On the other hand, once a method, or a device was developed to a stage where it would perform a desired function, Frank's interest turned to yet unsolved problems. The profits from his geophysical contracts and his electronic construction were invariably plowed back into his research where, in truth, his heart lay. He was a prolific inventor with at least 48 patents in the fields of electronics and sound. Among his patents were some on bore-hole surveying and logging, magnetic, electrical and seismic exploration for oil and, of interest in view of his most recent activities, a pioneer patent in the use of radar for altimetric purposes.

He was born in Placerville, California on March 12, 1891, the son of the late Dr. Charles Henry Rieber, esteemed former Dean of the College of Letters and Science at the University of California at Los Angeles, and Winifred Smith Rieber, a skilled professional artist well known for her portraits of famous philosophers, educators and scientists. Frank graduated from Berkeley High School and, in 1915, received his B.S. degree from the University of California.

A year's physical research for the Western Precipitation Company in Los Angeles had preceded his degree, after which he was engaged in the development of X-ray equipment in San Francisco until about 1923. During World War I he was a secretary of the California War Inventions Committee and a member of the Submarine Defense Commission. It was during his war work with sonic submarine detection and depth sounding that he became interested in the application of related techniques to the location of oil structures.

In 1924 he began research and operations with the refraction seismograph in California where he introduced methods of determining velocities of and depths to velocity layers of low contrast in the sedimentary series. Out of this period came a number of determinations of velocity still listed as standards in the literature, and maps of many of the shallow trends in California, many of which have since been confirmed by drilling and later reflection seismograph exploration. Ironically, the greatest tangible reward from this refraction program is alleged to have come to the company which bought a parcel of land in what is now the Rio Bravo-Greeley field, not because they were impressed with the generally high area mapped by Rieber, but because, according to the story, it was cheaper to buy the land than to pay for the damages caused by the large refraction shots.

When the crash of 1929 closed down seismograph operations in California, Frank Rieber, together with some associates, developed a method of recording sound on film for motion pictures which was not covered by the R.C.A. and Western Electric patents. Unfortunately, before they could market the method the studios had signed long term contracts with these companies.

Never one to be discouraged by set-backs, Frank returned in 1932 to the geophysical field where reflection seismograph work was in its infancy. After investigating the nature of reflections in some of the seismically complex areas of California, he became convinced that interference of waves reaching the geophones was the principal cause of poor seismic results in such areas. With characteristic enthusiasm he set about finding the cause of and cure for these interferences, turning his back on the lucrative commercial field to be exploited by others using conventional equipment in areas where reflections could be more easily obtained.

During the period from 1932 to 1935 Rieber investigated, and in some cases patented, methods of reducing surface disturbances at the shot and at the receiving point, methods of shortening wave transients and methods of separating waves arriving from different directions. The method combining most of the results of his research he called the "Sonograph," which involved recording the seismogram traces as reproducible sound tracks and subsequently reproducing them in variably phased combinations and through various filters to reduce the several types of interference, particularly that due to waves arriving from different directions.

In 1934 Frank Rieber joined the American Association of Petroleum Geologists and in 1936 the Society of Exploration Geophysicists and the next few years marked the height of his impact on the science of geophysics. He and his staff gave a series of papers on the Sonograph and on the complex geological conditions it was designed to evaluate. An effective speaker and a master of repartee, Rieber became a drawing card at any convention where he presented a paper, since his papers were always sufficiently controversial to elicit critical discussion. He introduced many novel features in his papers which added to their interest and effectiveness. Some of these were: spark photographs of reflection and diffraction of sound waves in the air to simulate the action of seismic waves in the earth; animated drawings of wave travel in the earth; and, as late as 1947, stereoscopic X-ray slides, with polarized glasses for the audience, to demonstrate a parallelism between the seismic art and the X-ray art.

Between 1934 and the end of 1938 Frank Rieber operated an average of about one and a half Sonograph crews in California and the Gulf Coast. One of Frank's handicaps was that no one oil company was interested in enough "difficult" areas to justify the continuous employment of the Sonograph, and he thus was seldom able to achieve the close cooperation and understanding with his clients which is such a valuable asset in exploration. Nevertheless, enough shooting was concentrated in some of these difficult areas to permit a prediction of structure, and a substantial number of these predictions were verified by drilling—at least two of these structures eventuating in oil fields.

In 1938 a wave of economy hit the oil business and, with plenty of "easy shooting" areas still available, the previously limited demand for the Sonograph disappeared entirely. Rieber was unprepared and unwilling to shelve the Sonograph, even temporarily, for the conventional seismograph and preferred to go out of business entirely rather than make the change.

Between 1939 and the time of his death Frank Rieber pursued various interests in electronics outside the geophysical field. Among his developments finding both industrial and military applications were a long-playing disc recorder and a sensitive pick-up, called the "Vibrotron," which was well adapted to telemetering.

Just before World War II he moved to New York where later he was a consulting engineer on war contracts and built large quantities of equipment for the Navy. Some of this work brought him in contact with the latest developments in radar and television, whose techniques he assimilated rapidly.

During the years since the Sonograph had been off the market, interest in difficult shooting areas had revived and much had been accomplished in solving the problems of West Texas and peat area shooting. No substitute for the Sonograph in separating interfering wave fronts had yet appeared,

however, and geophysical interpreters were seeking more and more information from seismograms and better ways of converting all the information on the seismograms into usable subsurface data. Rieber felt the time was ripe to devote his energy to these geophysical problems.

Utilizing his new familiarity with radar and television, he conceived a combination of these with the old Sonograph principle to speed up analysis of the reproducible seismogram to a practically instantaneous operation and to display the results as a cross-section on a cathode-ray screen. He made plans for such an analyzer and put into it every variable which a geophysical interpreter might desire. This new instrument he called "Geovision" and before he died he had the satisfaction of receiving the backing of at least one large oil company to help him develop this epic idea. Perhaps the time is now appropriate for the introduction of detailed electronic analysis of seismograms and if, as seems very possible, Geovision is developed after his death it will truly be a fitting monument to a man who clung to a vision ahead of his time in spite of disappointments and financial adversity.

Frank Rieber was by no means the single-purposed eccentric the above account may imply. To those who knew him well he was a mellow and entertaining companion, and his interest in the Humanities, derived from his philosopher father and his artist mother, was as great as his interest in the Sciences. His cheerful optimism seldom deserted him and his laboratories were always "happy work shops" in spite of all-too-frequent delays in the payroll. Frank took a fatherly interest in the members of his staff, inspired them in their work by his example, challenged them with unorthodox problems and answers, brought out the best in them with seemingly little effort and built up an *esprit de corps* wonderful to behold. In 1947 this spirit brought together in a reunion in Los Angeles over 90 per cent of the staff disbanded in 1938. Most of those present at the reunion were pursuing successful careers in geophysics or in the electronics industry, an indication that Frank Rieber will have left his mark in his chosen field through his former employees as well as through his direct technical contributions.

Frank Rieber has been called a genius and he has been called impractical; he has been called a spell-binder and he has been called a bore; he has been praised and he has been condemned, but he has never been ignored. Whatever else may be said about him, all agree he was unique. There will never be another Frank Rieber, and his passing marks a severe loss to the geophysical fraternity in terms of stimulation and inspiration.

PERSONAL ITEMS

At the twenty-ninth annual meeting of the American Geophysical Union, the tenth award of the William Bowie Medal was presented to Rev. Dr. J. B. Macelwane, S.J., Dean of the Institute of Technology at St. Louis University. The award, presented by Admiral Leo Otis Colbert, was made, "not only because of the success he (Father Macelwane) has achieved in his chosen field of seismology but also because of his active participation in the work of several geophysical organizations in this country and abroad."

In his citation, Admiral Colbert said, "He has directed major projects in seismology which have materially advanced our knowledge of earth physics and has conducted a score of minor projects which in the aggregate are equally important because of their basic potential value."

For the past three years Father Macelwane has served as Chairman of the Committee on Geophysical Education of the Society of Exploration Geophysicists.

In his response, Father Macelwane emphasized the importance of "unselfish cooperation" among scientists.

A complete account of the presentation appeared in *Transactions American Geophysical Union*, Vol. 29, No. 3 (June 1948).

GEORGE M. GILTINAN, a director of Seismograph Service Corporation, died of a heart attack while on vacation at Victoria Harbor, Ontario, Canada. Mr. Giltinan became a member of the Society of Exploration Geophysicists in 1945. A resident of Tulsa, he joined Seismograph Service in 1933 as a crew helper to acquaint himself with all phases of geophysics. He is survived by his wife, Florence, and a son, Francis Munro.

L. F. ATHY, Continental Oil Company, Ponca City, Oklahoma, was recently promoted from chief geophysicist to manager, geophysical department as a result of the recent expansion of the company's exploration division. J. A. Culbertson, former division geologist at Houston, is now assistant manager, geophysical department in Ponca City. W. Baxter Boyd, former district geologist, Ponca City, is now division geologist, Fort Worth.

Dr. Athy joined Continental in 1925 as assistant geologist, research department, and in 1929 was made assistant superintendent of the geophysical division. In 1932 he was named superintendent and was appointed chief geophysicist in 1936. Dr. Culbertson joined Continental in 1933 as a member of a seismograph crew; he became a party chief and was then named control geophysicist. He became assistant division geologist at Houston in June 1937, and division geologist in 1943.

ROBERT L. KIDD has been elected Vice President of Cities Service Oil Company. He is a member of the board of directors and manager of the company's land and geological division, also a director of Cities Production Corp.

REESE H. TUCKER has rejoined Cities Service Oil Company in the newly-created post of manager of geophysics. In announcing the appointment, R. L. Kidd, Vice President, explained that the purpose of the new post is to enhance the effectiveness of the company's overall program through increased co-ordination of the geophysical, geological and land work and to make possible closer supervision of geophysical planning and operations.

THOMAS H. GREEN, formerly geologist for Shell Oil Co., Inc., has resigned to join Sunray Oil Corp. as district geologist in Oklahoma City.

ROY F. BENNETT has been named Chief Geophysicist for the Sohio Petroleum Company. He was recently promoted from Division Geophysicist and will remain in Houston. Mr. Bennett was recently elected Secretary of the S.E.G. Houston Section.

FRED A. SMITH has been named Southern Division Geophysicist for Sohio Petroleum Company, Cyril B. Smith, Western Division Geophysicist, and Donald Crary, Geology and Geophysics Coordinator, according to a recent announcement by Roy F. Bennett, Chief Geophysicist.

H. WAYNE HOYLMAN, formerly with Gulf Research and Development Company, has accepted a position as chief geophysicist for Fairchild Aerial Surveys, Inc. in Los Angeles.

LORING B. SNEDDEN, formerly district geologist for The Texas Company at Bakersfield, has been promoted to assistant manager of the geophysical division in the producing department with headquarters in Houston.

ALEXANDER WOLF, Consulting Physicist, has moved his offices from 4708 Caroline St. to 2518 Huldy St., Houston 19, Texas.

C. W. BLAKEY, Seismograph Service Corporation, has been promoted from manager of the company's Middle East operations to manager of the company's newly created Rocky Mountain division with offices in Denver.

J. C. HEGGBLOM, geophysicist with Gulf Research and Development Company, has transferred from Nassau to Mozambique. He may be addressed Care of Mozambique Gulf Oil Company, Caixa Postal #69, Lourenco Marques, Portuguese East Africa.

LEWIS C. CRIDER resigned his position with The California Company in August of 1947, and is now geologist for Stanolind Oil and Gas Company. His address is Box 1680, Wichita Falls, Texas.

L. I. BROCKWAY, Supervisor of Geophysics with Canadian Gulf Oil Company, is located at 119 Sixth Ave. West, Room 301, Calgary, Alberta.

MARK MILSTEIN, Consulting Geophysicist, has moved his offices from New York City to 3712 Purdue Street, Dallas 5, Texas.

INDEX TO VOLUME XIII OF *GEOPHYSICS* FOR 1948

In order that this Index to Volume XIII may serve as a supplement to the Cumulative Index covering all publications of the Society from 1931 through 1946, it has been arranged in the same order as that adopted for use in the Cumulative Index. All technical material has been classified first, alphabetically by author; and second, by subject in accordance with the following outline:

Exploration, General
Seismology
  A. Areal
    1. Reflection Applications
    2. Refraction Applications
  B. General
  C. Instruments
  D. Theory and Technique
Gravimetric Methods
  A. Areal Surveys
  B. General
  C. Instruments
  D. Theory and Technique
Magnetic Methods
  A. Areal Surveys
  B. General
  C. Instruments
  D. Theory and Technique
Electrical Methods
Geochemical Methods
Surveying Techniques
Well Measurements
Case Histories
Miscellaneous
Society Round Table
  A. Author's Biographies and Photographs
  B. Constitution and By-Laws
  C. Meetings—Annual and Regional
  D. Membership Lists
  E. Memorials
  F. Officers
  G. Publications Received
  H. Secretary-Treasurer's Reports
  I. Statement of Ownership and Management
  J. Reviews and New Publications

INDEX BY AUTHOR

	Vol.	No.	Page
Armstrong, L. C. and Davidson, D. M. The Practical View in Geophysical Exploration for Metallic Ore Bodies	XIII	4	550
Atwater, Gordon I. The Discovery History of the University Oil Field, East Baton Rouge Parish, Louisiana	XIII	3	371
Bickel, H. C. A Note on Terrain Corrections	XIII	2	255
Boissonnas, Eric and Leonardon, Eugene G. Geophysical Exploration by Telluric Currents, with Special Reference to a Survey of the Haynesville Salt Dome, Wood County, Texas	XIII	3	387
Brant, A. A. Some Limiting Factors and Problems of Mining Geophysics	XIII	4	556
Daly, John W. An Instrument for Plotting Reflection Data on the Assumption of Linear Increase of Velocity	XIII	2	153
Davidson, D. M. and Armstrong, L. C. The Practical View in Geophysical Exploration for Metallic Ore Bodies	XIII	4	550
Delavault, Robert E. and Warren Harry V. Biogeochemical Investigations in British Columbia	XIII	4	609
de Witte, L. A. New Method of Interpretation of Self-Potential Field Data	XIII	4	600
Dix, C. Hewitt. The Existence of Multiple Reflections	XIII	1	49
Dresbach, C. H. Discussion—Multiple Reflections	XIII	1	57
Eckhardt, E. A. Geophysical Activity in the Oil Industry in the United States in 1947	XIII	4	529

	Vol.	No.	Page
Egyed, László. The Determination of an Infinite Inclined Dike from the Results of Gravity and Magnetic Surveys	XIII	3	437
Ellsworth, T. P. Multiple Reflections	XIII	1	1
Evjen, Haakon M. Theory and Practice of Low-Frequency Electro-Magnetic Exploration	XIII	4	584
Ewing, Maurice and Press, Frank. Low-Speed Layer in Water-Covered Areas	XIII	3	404
Frowe, Eugene. A Total Field Magnetometer for Mobile Operation	XIII	2	209
Fu, C. Y. and Gutenberg, B. Remarks on Multiple Reflections	XIII	1	45
Green, Cecil H. Integration in Exploration	XIII	3	365
Gutenberg, B. and Fu, C. Y. Remarks on Multiple Reflections	XIII	1	45
Haggerty, P. E. and Olson, R. W. Preliminary Results of a Study of Seismograph Sensitivity Requirements	XIII	1	86
Hanahén, Paul M. Explosives Accidents on Geophysical Crews	XIII	3	421
Hansen, Raúl F. Multiple Reflections of Seismic Energy	XIII	1	58
Heiland, C. A. How Can Geophysics Be of Better Service to the Mining Industry	XIII	4	535
Henderson, Roland G. and Zietz, Isidore. Analysis of Total Magnetic-Intensity Anomalies Produced by Point and Line Sources	XIII	3	428
Hubbert, M. King. A Line-Integral Method of Computing the Gravimetric Effects of Two-Dimensional Masses	XIII	2	215
——— Gravitational Terrain Effects of Two-Dimensional Topographic Features	XIII	2	226
Ittner, Frank. Discussion on Double Reflections	XIII	1	36
Johnson, Curtis. Remarks Regarding Multiple Reflections	XIII	1	19
Leonardon, Eugene G. and Boissonnas, Eric. Geophysical Exploration by Telluric Currents, with Special Reference to a Survey of the Haynesville Salt Dome, Wood County, Texas	XIII	3	387
Lester, O. C. Discussion of Multiple Reflections	XIII	1	51
Lewis, Wm. Bradley. Electrical Surveys of Some Shallow Salt Domes	XIII	4	595
Olson, R. W. and Haggerty, P. E. Preliminary Results of a Study of Seismograph Sensitivity Requirements	XIII	1	86
Reno, Duane H. and Taylor, Garvin L. Magnetic Properties of "Granite" Wash and Unweathered "Granite"	XIII	2	163
Schwartz, Geo. M. Some Aspects of the Ore Deposits Important in Geophysical Work	XIII	4	540
Sloat, John. Identification of Echo Reflections	XIII	1	27
Taylor, Garvin L. and Reno, Duane H. Magnetic Properties of "Granite" Wash and Unweathered "Granite"	XIII	2	163
Tripp, R. Maurice. Is It an Anomaly	XIII	3	443
Van Melle, F. A. Wave-Front Circles for a Linear Increase of Velocity With Depth	XIII	2	158
Walling, Dean. Notes on Multiple Reflections	XIII	1	55
Warren, Harry V. and Delavault, Robert E. Biogeochemical Investigations in British Columbia	XIII	4	609
Waterman, Joseph C. Multiple Reflection Evidence	XIII	1	41
Waters, Kenneth H. An Improved Method of Land Surveying for Use in Brush-Covered Areas	XIII	2	259
West, Thomas S. Deep Electrical Prospecting—A Reply	XIII	1	97
Worzel, J. L. Ocean Bottom Sampler for Ships Under Way	XIII	3	452
Wyckoff, R. D. The Gulf Airborne Magnetometer	XIII	2	182
Yüngül, Sulhi. Deep Electrical Prospecting—A Discussion	XIII	1	92
Zietz, Isidore and Henderson, Roland G. Analysis of Total Magnetic-Intensity Anomalies Produced by Point and Line Sources	XIII	3	428

INDEX BY SUBJECT

Exploration—General

Geophysical Activity in the Oil Industry in the United States in 1947. E. A. Eckhardt	XIII	4	529
Integration in Exploration. Cecil H. Green	XIII	3	365
Is It an Anomaly? R. Maurice Tripp	XIII	3	443
How Can Geophysics Be of Better Service to the Mining Industry. C. A. Heiland	XIII	4	535

	Vol.	No.	Page
B. Constitution and Bylaws			
Constitution and Bylaws	XIII	2	309
Recommended Amendments to the Constitution and Bylaws	XIII	2	305
C. Meetings			
Abstracts of Papers Read at the Pacific Coast Meeting	XIII	2	299
Annual Award for Best Paper	XIII	3	520
Houston Meeting of the American Physical Society and the Society of Exploration Geophysicists, The	XIII	1	146
Minutes of the Annual Business Meeting	XIII	3	507
Organization of the Ark-La-Tex Geophysical Society, Report on the	XIII	1	141
Organization of the Dallas Geophysical Society	XIII	1	144
Organization of the Society of Exploration Geophysicists, Houston Section	XIII	1	143
Pacific Coast Meeting	XIII	1	145
Papers Presented at the Eighteenth Annual Meeting	XIII	3	493
Papers Presented at Meetings of the Local Sections	XIII	2	302
———	XIII	3	521
D. Membership Lists			
Membership Applications Approved for Publication	XIII	1	136
———	XIII	2	297
———	XIII	3	528
———	XIII	4	651
Membership List	XIII	2	318
E. Memorials			
Kendall, Graham D., by Francis F. Campbell	XIII	3	526
Rieber, Frank, by Curtis H. Johnson	XIII	4	659
F. Officers			
Nominees for 1949–1950 Executive Committee	XIII	4	646
Officers for the Year Ending March, 1949	XIII	3	492
G. Publications Received	XIII	1	122
———	XIII	2	289
———	XIII	3	486
———	XIII	4	642
H. Secretary-Treasurer's Reports			
Treasurer's Report on Financial Condition of Society of Exploration Geophysicists	XIII	3	510
I. Statement of Ownership	XIII	1	148
J. Reviews and New Publications	XIII	1	116
———	XIII	2	281
———	XIII	3	480
———	XIII	4	639

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TULSA
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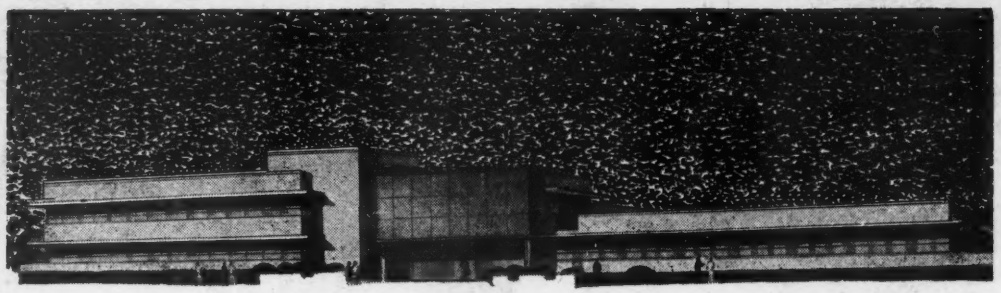

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